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Test Methods for Composites a Status Report

Volume II. Compression Test Methods

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Final Report

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16. Abstract

This document embodies the results of an evaluation of current test methods for compression properties of composite materials consisting of high modules, high strength fibers in organic matrix materials. Mechanical testing is an important step in the "building block" approach to design of composite aircraft structures. The document provides a source of information by which the current compression test methods for advanded composites can be evaluated and from which test methods which appear to give good-quality test data can be selected. Problems with the available compression test methods are also addressed as a means of providing recommendations for future research.

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PREFACE

This document is Volume II of three volumes which have been developed to provide an assessment of mechanical property test methods for organic matrix composite materials. The present volume presents a review and evaluation of test methods for compression properties of fiber reinforced composite materials. Two companion documents, Volume I on Tension Test Methods and Volume III on Shear Test Methods, have also been prepared.

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EXECUTIVE SUMMARY

This document, which constitutes Volume 2 of a three volume set, provides an evaluation of current test methods for compression properties of "advanced" composites constructed of high modulus, high strength fibers embedded in organic matrix materials such as epoxies. Mechanical testing for various structural properties is one of several essential steps in the design of composite aircraft structures. Companion volumes addressing: Tension Testing (Volume 1) and; Shear Testing (Volume 3) of composite materials, are also available. The intention is to provide a comprehensive source of information by which the current test methods for these types of property tests can bc evaluated and from which test methods which appear to give good-quality test data can be selected.

The document provides: (1) a comprehensive review of performance features, advantages and negative aspects of various test methods which have been introduced for obtaining compression properties of composite materials; (2) an extensive annotated bibliography covering most documented test method development activity which has taken place since the introduction of advanced composites in the mid 1960's; (3) a ranking of the commonly used test method for tensile properties, and: (4) an assessment of problem areas that continue to exist in the available test methods.

The compression testing of composite materials, particularly the higher stiffness, higher strength composites (e.g., unidirectionally-reinforced polymers as opposed to fabric- and random mat-reinforced polymers) is still very much an emerging technology. Although compression testing of composite materials has been performed for many years, in the past it was done on a somewhat undisciplined basis. Only recently has significant concern been given as to whether available test procedures are actually meaningful in terms of generating useful design data. Determining representative compressive strengths is the principal problem, stiffness measurements being considerably less difficult to perform. Together with the historical lack of rigor in experimentally characterizing compression properties, relatively little rigorous analytical investigation has been performed to date. Almost all of this limited analysis has been done in the past few years, and for the most part is not yet very conclusive. The motivation in performing analytical studies is that once the procedure is developed, large numbers of parametric variations can be run very quickly

and inexpensively, relative to laboratory experiments. Thus, the goal, not yet attained, is to use analysis to predict test specimen response to the large number of potentially significant influencing factors, e.g., test fixture geometry and precision, tabbing variations, specimen alignment, etc., and then to perform actual experiments using only those parameters that are predicted to have a significant influence on the test results.

The Celanese compression test method, first standardized by ASTM in 1975, remained as the only composite material compression testing standard until 1987 when the IITRI and Sandwich Beam methods were added as Methods B and C to this ASTM Standard D 3410. For the Celanese and IITRI test methods, the specimen is shear-loaded through tabs bonded to each end of the straight-sided specimen.

During the latter half of the 1980's, several groups continued to experiment with direct end-loading of composite specimens also. Since ASTM Standard D 695, originally developed for unreinforced plastics in 1942, is also an end-loading test method, the composite end loading test methods have recently come to be called "Modified D 695" test methods, even though they usually bear little resemblance to the ASTM Standard. The Boeing Company has become best known for their version, which has now also been adopted as a SACMA (**S**uppliers of **A**dvanced **C**omposite **M**aterials **A**ssociation) Recommended Test Method, and is being considered for standardization by ASTM as well.

Many other modifications of the basic shear-loaded and end-loaded test methods have also been introduced during the past few years, primarily by individual university and industry groups. While some appear very promising, most have not yet been adequately evaluated on a broad basis, and thus many uncertainties associated with their use remain. A summary of the various compression test methods available, and their relative virtues, is presented in the body of the report. The general conclusion is that, while no existing compression test method is ideal, the IITRI test method or one of its variations is perhaps the most reliable and versatile. Visual, and even microscopic, observation of the failure mode is not a reliable indicator of the validity of an individual test result. Variations are too subtle. Correspondingly, the occurrence of a buckling failure, which negates a valid compression test, cannot usually be visually detected either during testing or in a post-failure analysis. Back-to-back strain measuring instrumentation is necessary.

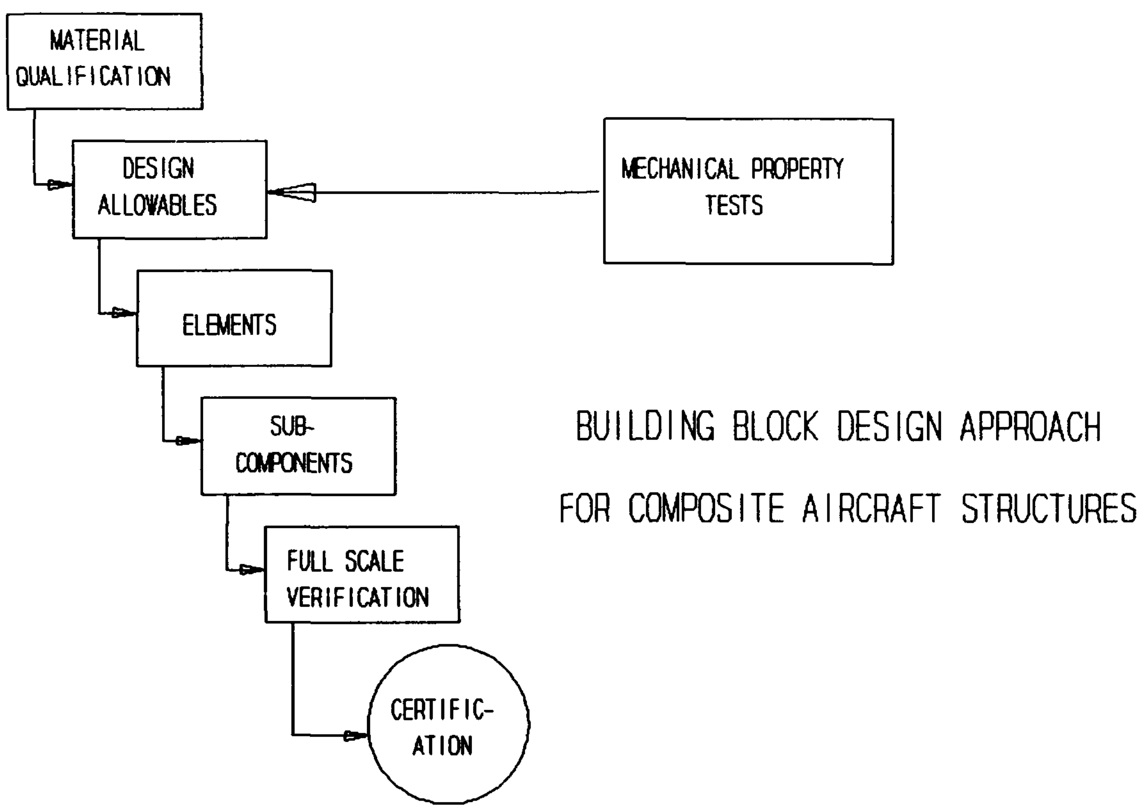
In summary, much more detailed experimental and analytical study of compression test methods remains to be performed before the composite materials community will be

able to standardize on one or two test methods.

OVERVIEW

GENERAL REMARKS

This document which constitutes Volume 2 of a three volume set, provides an evaluation of the state of the art of current test methods for obtaining compression properties of "advanced" composites constructed of high modulus, high strength fibers embedded in organic matrix materials such as epoxies. Mechanical testing is an important step in the "building block" approach to design of composite aircraft structures, as illustrated in the Figure below. Companion volumes addressing: Tension Testing (Volume 1) and; Shear Testing (Volume 3) of composite materials, are also available. The intention is to provide a source of information by which the current test methods for these types



Mechanical Property Testing in Composite Aircraft Design

of property tests can be evaluated and from which test methods which appear to give good-quality test data can be selected.

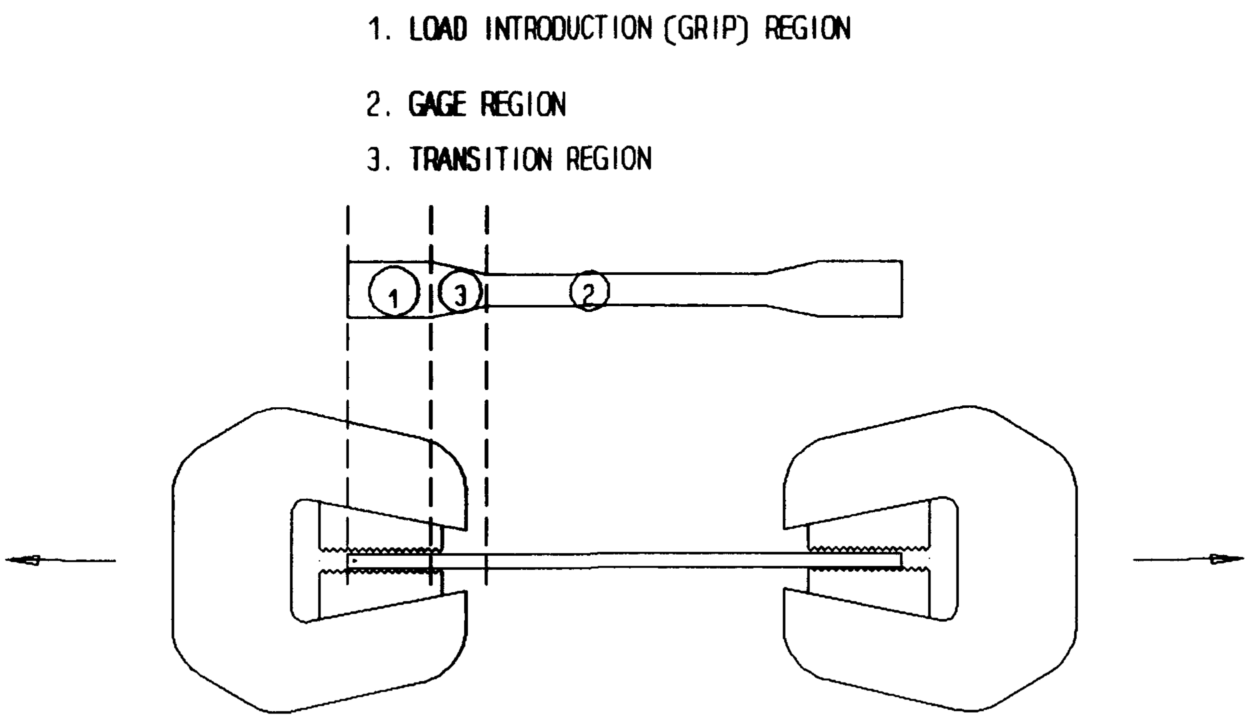
Mechanical property testing of advanced composites has been under development ever since the introduction of such materials nearly a generation ago. The first major conference on test methods for advanced composites, for example, took place in 1969 and culminated in ASTM Special Technical Publication STP 460 which summarized results from a number of DoD programs that were ongoing at that time. The methods which were reported on that occasion formed the basis for a number of test methods which are still in use.

The methodology for obtaining mechanical properties of such materials contains a number of inadequacies and is in need of continuing development. The purpose of this discussion is to review the issues which are significant drivers in efforts toward improved testing methodology, in order to provide a framework for evaluating the state of the art.

OBSERVATIONS ON MECHANICAL PROPERTY TESTING OF COMPOSITES

Mechanical property measurements in structural materials can be characterized in terms of three regions in the test specimen (illustrated in the following Figure for a generic tension test): (1) a load introduction or gripping region, where large stress peaks associated with the load introduction method are compensated for by a relatively large loaded area; (2) a central ("gage") region of relatively small loaded area where failure is meant to be produced, and; (3) a transition region joining the gage and grip regions. (A clear cut transition region, (3), is not present in many types of test specimen).

The gripping region is characterized by complex loading features, often involving very peaky stress distributions associated with hard contact points. Three dimensionality in the form of stress variations through the thickness is frequently present in the grip region. In the representative case shown on the following page, the load is introduced through the hard teeth of serrated surfaces of a wedge grip which results in through-the-thickness shearing; in the transition region this translates into spreading of the load in the lateral direction via in-plane shearing. Softening layers which may include tabs, thin sandpaper sheets or other approaches, may be present in the grip region. In beam-type specimens used for short beam shear and flexure testing, hard contact points represented by small-



Elements of Generic Test Specimen

radius rods of a relatively rigid material such as steel may be present that give rise to severe stress peaks in the load introduction region which are unrelated to the desired stress state.

The ideal mechanical property test specimen would provide a large effective loaded area in the grip region to compensate for stress peaks caused by the gripping arrangement, while allowing the stresses in the gage region to approach a uniform condition of high stress which ensures that failure takes place in that region. Furthermore, sufficient volume of test material should be involved in the gage region to provide an adequate sampling of the variability which is characteristic of the material being tested. For various reasons, such an ideal form of behavior is hardly ever achieved in practical test specimens for composite materials.

Specific problems which hamper successful mechanical property measurements in organic matrix composites will be summarized at this point.

Measurement of mechanical properties in organic-matrix composites is difficult because

of a general lack of ductile response together with large differences in the mechanical strengths of such materials for stresses in various directions. The problem is relieved somewhat for materials reinforced in more than one direction because the strength differences are considerably less in such cases, but the requirements of the technology are currently set by those for unidirectionally reinforced materials.

For the situation shown in the preceding Figure, for example, a metallic specimen will be relatively insensitive to the indentations caused by the serrations of the loading grips, and no special difficulty will be caused by the details of the transition region, since local yielding will cause the stress at any cross section to tend toward a uniform "P-over-A" value (i.e. nominal stress defined by load divided by section area) applicable to the section under consideration; these "P-over A" stresses will be obliged to have their maximum values in the gage region by the mechanics of the situation, specifically the fact that the smallest section occurs there, so that satisfactory confinement of failure to the gage region will be obtained. Accordingly, there is little need for concern over the possibility of not obtaining representative failures in metallic test specimens.

In the case of organic composites reinforced with high strength/high modulus fibers, on the other hand, achievement of representative failure is difficult. For example, it was found early in the development of the technology of advanced composites that for tension and compression testing, width-wise tapering to form a stress-focussing transition region (see the preceding Figure) usually leads to splitting failures in the tapered region long before a valid failure can be obtained in the gage region. This tendency appears to be related to excessively low shear strength of organic matrix composites in comparison with their tensile or compressive strength in the fiber direction. For the case of tension testing, the problem was dealt with in early efforts by the introduction of rectangular (i.e. uniform width) test coupons with thickness-wise bonded-on doublers (i.e. tabs) at the ends, through which the load was sheared in. This is generally accepted practice for tensile testing, as well as a number of compression test specimen designs.

On the other hand, the processes governing the behavior of the tabs lead to high stress peaks at the gage ends of the tabs, so that failures near or inside the tabs are quite likely and are commonly observed. Even though a consensus developed for the use of tabs, they obviously do not achieve the type of behavior described previously as the ideal of a test specimen design. Moreover, a number of practical difficulties are associated with tabs.

Debonding of tabs is certainly not unusual, and is especially troublesome for test situations involving high temperature and humidity. In other words, the use of tabs as a supposed cure for the problem of splitting in width tapered tension and compression specimens is not a completely adequate solution. This kind of poor choice of alternatives characterizes many situations in the testing of composites.

An additional complication is caused by the fact that designers of composite structures need a much larger variety of property measurements than those working with metals. In the latter case a single yield strength based on a tension test is adequate for predicting yield-related failure in tension, compression and shear loading, due to the fact that failure modes corresponding to various loading modes in metals can be traced back to the same yield condition through the use of Mohr's circle transformations. In composites, the design can generally not proceed without independent measurements of tension, compression and in-plane shear properties, both modulus and strength, as well as a number of other properties, each of which has a unique failure mode that cannot be inferred from other loading modes.

In addition to increased effort corresponding to the requirement for a greater variety of test measurements, special difficulties specifically associated with compression testing arise. These have to do with the fact that properties often have to be measured on thin-gage specimens which tend to be prone to Euler column buckling prior to valid compression failure of the test material.

Greater variability of fibrous composites is also a factor which leads to problems in mechanical property testing. Not only are structural metals produced from extremely mature technology, but they are formed in large lots of highly homogenized constituents, and uniformity of strength and modulus is to be expected with them. Composites are built up by mechanical placement of constituent reinforcement and matrix components using methods which cannot be controlled to nearly the same level of uniformity. Reflection of this variability in mechanical property test data is a legitimate result, but variability may also be an undesirable characteristic of the test method. Lack of consistency between test results obtained on the same lot of material from different organizations is a common occurrence.

FACTORS AFFECTING PERFORMANCE OF TEST SPECIMENS

In view of the abc ›e comments, certain specific issues can be cited as a basis for judging which of the current test methods are well in hand vs. which are in need of additional development effort. These include: (1) whether or not the test produces a valid failure mode; (2) whether the stress distribution in the specimen is such as to insure failure in the gage region as opposed to the development of spurious failures; (3) sensitivity of the test results to practical considerations such as specimen machining tolerances, specimen surface finish requirements and accuracy of alignment of the specimen in the test machine.

These issues are clarified in the following discussion.

Failure Modes for Various Types of Loading

Except for buckling in the case of compression specimens, spurious failures are usually the consequence of severe stress concentrations in the load introduction region. Some obvious examples can be stated.

Tabbed specimens tend to fail in many cases at the tab ends or inside the tabs. Stress analysis shows that stress peaks which occur there are unacceptably severe unless the tab ends are bevelled at angles as low as 10°. Failures in the t ıb bonds can be expected at high temperature and humidity because of the limitations of typical adhesives. Such failures may be less likely in compression testing because of the compressive nature of transverse extensional stress to which bond materials tend to be sensitive.

Many types of compression specimen are subjected to column buckling failure because of the need for thinness in the specimen. End loaded compression specimens often fail by "brooming", i.e. splitting apart of fibers near the loading platens. It is not clear that the mechanism of brooming is adequately understood.

Width tapered specimen shapes tend to fail prematurely because of shear stresses associated with the tapered portion. With cross-plied materials, however, width-wise tapering is somewhat more successful because the spurious stresses associated with tapering tend to be relatively lower and because the cross reinforcement tends to

strengthen the material against undesirable failures.

Beam-type specimens (flexure and short beam shear tests) tend to fail prematurely due to contact stresses near loading points which are non-representative of desired failure modes.

Status of Stress Analysis in Test Specimens

Stress analysis has been carried out for some width tapered specimens, which show that linearly tapered ("bowtie") shapes, as well as so-called "streamline" shapes give better performance that "dogbone" shapes such as the ASTM D638 specimen which was originally developed for plastics but has often been used for testing of composites. Comparison of analytical and experimental results have confirmed that the D638 is prone to failures at the end of the tapered region where the stresses are maximum.

Stress analyses of tabbed specimens have shown that severe stress peaks occur at the ends of the tabs, and that the use of bevelled ends on the tabs is probably not effective for tab angles greater than 10°. Linear elastic analyses of the effects of tab material indicate large differences in peak stresses for steel tabs vs. fiber glass tabs which are not necessarily reflected in test results. Ductility of the adhesive used to bond tabs, which probably has not been investigated analytically to date, may be a more important factor than the properties of the tab material.

A number of buckling analyses of compression specimens have been performed, which have given considerable guidance on requirements for avoiding premature buckling failures. Brooming which is a frequent problem in end loaded compression specimens is probably not well understood and needs further investigation. Sandwich beam compression specimens have been analyzed to examine the degree of restraint between the core and composite skin being subjected to compression testing.

Considerable stress analysis has been reported for shear test specimens. In the case of in-plane shear tests, stress analysis has been conducted on a number of specimen designs such as the $\pm 45°$ tension test, the Iosepescu test, the rail shear test, the picture frame shear test, the double notched shear specimen and others. The double-notched shear specimen is a good example of a design based on an oversimplified concept of the stress state in the specimen which is not even approximately achieved in practice. Because of extremely high stress peaks in such specimens, all test results obtained from

them must be considered suspect. Stress analyses have also been performed on beam-type specimens such as the short beam shear test for transverse shear properties to determine the effect of stress peaks around the load points.

Specimen Machining and Alignment Effects

Machining tolerances for test specimens may be somewhat arbitrary. A rational basis for setting tolerances may be developed from parametric studies of the effects of specimen machining errors, i.e. computer modelling of the influence of non-planarity and non-paralellism of specimen surfaces on the stress state in the specimen. Such studies have been presented in the literature to some extent, especially in the case of compression testing where the concern for sensitivity of test results to specimen imperfections is generally prevalent. Specimen alignment is a crucial feature of many test methods, again, especially in the case of compression testing. Some testing jigs have provided special features for insuring precise specimen alignment. As in the case of machining tolerances, requirements for alignment are often specified arbitrarily, and there is a need for combined experimental and analytical studies to establish these requirements more rationally in several types of test.

FORMAT OF THE DOCUMENT

The preceding discussion illustrates the type of information that this report is intended to provide. Each of the 3 volumes a provides comprehensive review of most of the test methods which have been used for obtaining structural properties of composite materials over the years. These include most of the standard methods which have been adopted by ASTM, SACMA (Suppliers of Advanced Composite Materials Association) as well as other organizations, in addition to a number of methods which have become generally popular in the industry but have not been adopted as standards.

The format of each volume includes the following:

1. EXECUTIVE SUMMARY (constitutes a brief summary of the state of testing methodology for the type of testing addressed in the volume under consideration)

2. INTRODUCTION

3. SUMMARY AND RECOMMENDATIONS (includes a relative ranking of test methods in each category, and recommendations for effort needed to correct deficiencies)

4. DETAILED DISCUSSION (a detailed discussion of each test method under consideration, including: failure characteristics of the specimen; discussion of the status of stress analysis for the specimen considered and conclusions to be drawn about the effect of stresses on test results and; practical considerations such as sensitivity to machining tolerances, specimen alignment requirements, etc)

In addition, an appendix is included with each volume which contains an annotated bibliography covering all of the available literature back to the mid 60's which it was practical to review within the scope of this effort.

TECHNICAL SUMMARY

The compression testing of composite materials, particularly the higher stiffness, higher strength composites (e.g., unidirectionally-reinforced polymers as opposed to fabric- and random mat-reinforced polymers) is still very much an emerging technology. Although compression testing of composite materials has been performed for many years, in the past it was done on a somewhat undisciplined basis. only recently has significant concern been given as to whether available test procedures are actually meaningful in terms of generating useful design data. Determining representative compressive strengths is the principal problem, stiffness measurements being considerably less difficult to perform.

Associated with the historical lack of rigor in experimentally characterizing compression properties, relatively little rigorous analytical investigation has been performed to date also. Almost all of this limited analysis has been done in the past few years, and for the most part is not yet very conclusive. The motivation in performing analytical studies is that once the procedure is developed, large numbers of parametric variations can be run very quickly, and inexpensively, relative to laboratory experiments. Thus, the goal, not yet attained, is to use analysis to predict test specimen response to the large number of potentially significant influencing factors, e.g., test fixture geometry and precision, tabbing variations, specimen alignment, etc., and then to perform actual experiments using only those parameters that are predicted to have a significant influence on the test results.

The Celanese compression test method, first standardized by ASTM in 1975, remained as the only composite material compression testing standard until 1987 when the IITRI and Sandwich Beam methods were added as Methods B and C to this ASTM Standard D 3410. For the Celanese and IITRI test methods, the specimen is shear-loaded through tabs bonded to each end of the straight-sided specimen.

During the latter half of the 1 980's, several groups continued to experiment with direct end-loading of composite specimens also. Since ASTM Standard D 695, originally developed for unreinforced plastics in 1942, is also an end-loading test method, the composite end loading test methods have recently come to be called "Modified D 695" test methods, even though they usually bear little resemblance to the ASTM Standard. The Boeing Company has become best known for their version, which has now also been adopted as a SACMA Recommended Test Method and is being considered for standardization by ASTM as well.

Many other modifications of the basic shear-loaded and end-loaded test methods have also been introduced during the past few years, primarily by individual university and industry groups. While some appear very promising, most have not yet been adequately evaluated on a broad basis, and thus many uncertainties associated with their use remain.

A summary of the various compression test methods available, and their relative virtues, is presented in Table 1. The general conclusion is that, while no existing compression test method is ideal, the IITRI test method or one of its variations is perhaps the most reliable and versatile. Visual, and even microscopic, observation of the failure mode is not a reliable indicator of the validity of an individual test result. Variations are too subtle. Correspondingly, the occurrence of a buckling failure, which negates a valid compression test, cannot usually be visually detected either during testing or in a post-failure analysis. Back-to-back strain measuring instrumentation is necessary.

In summary, much more detailed experimental and analytical study of compression test methods remains to be performed before the composite materials community will be able to standardize on one or two test methods. In the meantime, it is hoped that the guidelines and suggestions offered in this report will be useful.

Table 1. Status of Compression Test Methods

	Method	Status	Rank
Shear-Loaded Specimen Test Methods			
1.	Celanese (ASTM D 3410)	Long-established ASTM standard. Results are very sensitive to accuracy of fixture and test procedure.	2
2.	Wyoming-Modified Celanese	Cone grips replaced by tapered cylindrical grips. Post and bearing alignment replaces sleeve. Reduced fixture cost. Wider specimen.	1
3.	IITRI (Illinois Institute of Tech. Research Institute (ASTM D 3410))	An ASTM standard since 1987. Tapered flat wedges. Post and bearing alignment. Massive, relatively expensive fixture. Wide, thick specimen can be tested.	1
4.	Wyoming-Modified IITRI	Smaller, more simply fabricated version of standard IITRI fixture. Wyoming-Modified Celanese perhaps a better alternative.	2
End-Loaded Specimen Test Methods			
5.	ASTM D 695	Designed for unreinforced plastics. Not very suitable for composites.	3
6.	Modified ASTM D 695	Currently a Boeing and SACMA recommended method. Deviates extensively from the ASTM standard. Short (0.188") gage length.	2
7.	Wyoming End-Loaded, Side-Supported	Very simple fixture. Standard gage length. Limited by end crushing to low and medium strength materials unless end tabs are used.	2
8.	RAE (Royal Aircraft Est.)	Thickness-tapered specimen. Simple fixture. Few detailed results available.	2
9.	Block Compression	Limited by end crushing to low strength composites unless end reinforcement is used.	3
Sandwich-Beam Specimen Test Methods			
10.	ASTM D 3410, Method C - Flexure	Large specimen. Expensive to fabricate. Simple fixture. Reliable results if specimen is properly designed to prevent core failure.	3
11.	Sandwich Column, Axial Loading	Must fabricate sandwich laminate. End crushing a problem.	3
12.	Mini-Sandwich Column Axial Loading	Newly developed. Little data available. Promise of high measured strengths.	2

1. INTRODUCTION

The proper compression testing of composite materials, particularly of the higher strength composites, remains a major concern. Although compression testing of composite materials in general has been performed for many years, only in the past few years has there been significant concern with using proper test methods and procedures. In earlier times, compressive properties were usually considered as being secondary to axial and transverse tensile and inplane shear properties, and often not even measured. When compressive properties design data were required, it was usually adequate to assume strength values, the compressive strengths being known to be at respectable levels relative to the corresponding tensile values. However, as newer design applications have pushed the capabilities of the various composite materials towards their limits, it has become much more important to measure directly the compressive strengths of these materials. Thus, there has been a rapid introduction of new compression test methods during the past five or more years. Fortunately, the situation is now stabilizing, new methods being introduced at a much slower rate at the present time. However, there has not yet been time to fully assess the various new test methods, and to adequately compare them with each other. As a result, much confusion exists within the composite materials testing community, with much erroneous information being circulated, and many conflicting results being published.

The purpose of this status report is to present a thorough review of the available literature, and to offer an assessment of the current status of composite material test methods. The Appendix contains an annotated bibliography of the works reported in the open literature. Many of these bibliographical entries are also directly referenced in the discussion presented in the body of this survey report. Those are the ones that have been marked with an asterisk in the list of references, so that the interested reader can refer to the bibliography for more information. Descriptions of the various test methods, discussion, and recommendations are based on the review of these works, and the authors' own experiences in compression testing. No additional research was conducted for the preparation of this report.

An Executive Summary has been presented in the previous section of this survey report. In the following section, a summary of each test method is given, followed by a list of recommendations as to where additional work appears to be needed.

For each test method summarized, the following points are addressed, in this indicated order:

1. Problems associated with load introduction and free edges.
2. Uniformity of the stress field.
3. Sensitivity to imperfections.
4. Acceptability of failure modes.
5. Simplicity and adequacy of data reduction procedures.
6. Specimen preparation and fixture requirements.
7. Consistency of results and other information.

Detailed discussions of the specific compression test methods are then given in the sections which follow. These detailed discussions can be assumed to be applicable to all fiber-reinforced composite material systems, except in those special cases noted where some characteristic difference for a specific material exist. While the main emphasis of the present review is on polymer-matrix composites, much of the discussion is equally applicable to other composite material forms as well, including both metal-matrix and ceramic-matrix composites. The specific compression test methods to be discussed include the following:

<u>Shear-Loaded Specimen Test Methods</u>

1. Celanese
2. Wyoming-Modified Celanese
3. IITRI (Illinois Institute of Technology Research Institute)
4. Wyoming-Modified IITRI

<u>End-Loaded Specimen Test Methods</u>

5. ASTM D 695
6. Modified ASTM D 695
7. Wyoming End-Loaded, Side-Supported (ELSS)
8. RAE (Royal Aircraft Establishment)
9. Block Compression

Sandwich-Beam Specimen Test Methods

10. ASTM D 3410, Method C - Flexure
11. Sandwich Column Axial Loading
12. Mini-Sandwich Column Axial Loading

For each of the test methods listed above, the following issues will be addressed in detail:

a. GENERAL DESCRIPTION OF THE TEST METHOD - A description of the test method and the procedures commonly used, including photographs and/or line drawings of specimens and fixtures.

b. STRESS STATES AND FAILURE MODES - The nature of the stress state induced in the specimen, including representative results of available stress analyses. This includes disturbances and stress peaks at critical locations such as loading points (including the effects of grips, fixture anomalies, specimen tabs and tab anomalies, and special problems associated with hot and/or wet testing). Common failure or damage modes and consistency of results are also addressed.

c. OTHER REQUIREMENTS AND MODIFICATIONS - Other considerations such as specimen machining tolerances, alignment requirements, and fixture quality will be addressed. Modifications of existing configurations and procedures will be suggested, for improving test method performance.

2. SUMMARY AND RECOMMENDATIONS

Table 1 indicates the current status of the various compression test methods currently available, along with a relative ranking of their general acceptability. The ranking is based on factors such as ease of fixture handling, ease of specimen preparation, cost of fixture and specimen, sensitivity of the data to fixture accuracy and test procedure, simplicity of data reduction and acceptability of observed failure mode. A brief summary is also presented here for each of these test methods, which will be discussed in greater detail in subsequent sections of this survey report. This summary follows the seven-point outline defined in the INTRODUCTION. Both general and specific recommendations as to areas where additional investigation is needed are then presented at the end of this section.

2.1 SHEAR-LOADED SPECIMEN TEST FIXTURE CONFIGURATIONS

2.1.1 Celanese Compression Test Method

1. Problems Associated With Load Introduction and Free Edges

Both the test fixture and the specimen must be precision machined to provide proper loading. The very narrow specimen used (0.25") emphasizes influences of free edges.

2. Uniformity of the Stress Field

Stress concentrations exist at the tab ends, typical of shear-loaded compression specimen test methods to be discussed later. Induced bending and buckling due to cone-in-cone grip arrangement is a special problem with this fixture.

3. Sensitivity to Imperfections

The specimen must be of a precise thickness (0.157" ± 0.002") in the tabbed regions. Corresponding machining operation can induce nonsymmetries.

4. Acceptability of Failure Modes

No better or wor han all other shear-loaded specimen test methods. The narrow specimen width does not appear to induce anomalous failure modes.

5. Simplicity and Adequacy of Data Reduction Procedures

Simple σ = P/A stress calculation is needed. Strain gage(s) rather than extensometers are typically used to measure strains, because of confined space available.

6. Specimen Preparation and Fixture Requirements

Specimen thickness in tabbed region is critical. A precision fixture is necessary to insure proper fit of the cone-in-cone gripping arrangement.

7. Consistency of Results and Other Information

Because of the sensitivity to specimen thickness and fixture precision, test results reported in the literature show severe scatter, indicating the unforgiving nature of this test method.

2.1.2 Wyoming-Modified Celanese Compression Test Method

1. Problems Associated With Load Introduction and Free Edges

No special problems exist, only those typically associated with all shear-loaded compression test methods to be discussed later. The specimen is 0.50" wide, as commonly used for most of the competing methods, and thus influences of free edges are similar.

2. Uniformity of the Stress Field

Stress concentrations exist at the tab ends, typical of shear-loaded compression specimen test methods. The specimen gripping system is similar to that of the IITRI fixture, with tapered cylindrical wedges rather that flat wedges being used.

3. Sensitivity to Imperfections

No special problems exist, only those typically associated with all shear-loaded compression test methods. A rigid post-and-bearing alignment system helps reduce the sensitivity to specimen imperfections.

4. Acceptability of Failure Modes

No better or worse than all other shear-loaded specimen test methods.

5. Simplicity and Adequacy of Data Reduction Procedures

Simple $\sigma = P/A$ stress calculation is necessary. An extensometer rather than a strain gage can be readily used to measure strains, if desired, because of the open nature of the fixture.

6. Specimen Preparation and Fixture Requirements

No special specimen preparation is necessary. The standard fixture does use a 4.5" long specimen, rather than the 5.5" long specimen used in the Celanese and IITRI fixtures. But since the gage length is still a standard 0.50", a longer specimen can be cut down for use, if desired.

7. Consistency of Results and Other Information

Test averages and data scatter are consistent with those obtained using the IITRI test method. The advantage is a very compact (less than 10 lb.), easy to use, and relatively inexpensive test fixture.

2.1.3 IITRI Compression Test Method

1. Problems Associated With Load Introduction and Free Edges

No special problems exist, only those typically associated with all shear-loaded compression test methods to be discussed later. This fixture is unique in that it is the only commonly used shear-loaded compression fixture capable of testing a specimen wider than 0.50". Although various fixture versions do exit, an IITRI fixture should be capable of testing a specimen up to a full 1.5" wide, and as thick as 0.60" at the tabbed ends.

2. Uniformity of the Stress Field

Stress concentrations exist at the tab ends, typical of shear-loaded compression specimen test methods. The specimen is gripped via tapered flat wedges, in a manner similar to most tensile mechanical wedge grips. Thus, gripping problems are similar.

3. Sensitivity to Imperfections

No special problems exist, only those typically associated with all shear-loaded compression test methods. A very rigid post-and-bearing alignment system helps reduce the sensitivity to specimen imperfections.

4. Acceptability of Failure Modes

Failure modes are similar to those observed in other shear-loaded specimen test methods.

5. Simplicity and Adequacy of Data Reduction Procedures

Simple σ = P/A stress calculation is necessary. It is difficult, but not impossible, to use an extensometer rather than a strain gage to measure strains, because of the long reach distance into the narrow (0.5") gap between massive fixture halves.

6. Specimen Preparation and Fixture Requirements

A standard straight-sided, tabbed specimen geometry is used. The standard IITRI fixture accommodates a 5.5" long specimen, although a shorter specimen can be used, the same as for the Celanese fixture. However, much wider specimens can be accommodated, and specimen thickness is not restricted as for the Celanese fixture.

7. Consistency of Results and Other Information

Test averages and data scatter are at least as good, and often better, than those obtained using any of the other compression test methods.

2.1.4 Wyoming-Modified IITRI Compression Test Method

1. Problems Associated With Load Introduction and Free Edges

No special problems exist, only those typically associated with all shear-loaded compression test methods as discussed later. This fixture uses flat wedge grips, the same as the standard IITRI fixture. The standard specimen width is 0.50", and the length 5.5", although special fixtures of other capacities have been utilized.

2. Uniformity of the Stress Field

Stress concentrations exist at the tab ends, typical of shear-loaded compression specimen test methods. The specimen is gripped via tapered flat wedges, in a manner similar to most tensile mechanical wedge grips. Thus, gripping problems are similar.

3. Sensitivity to Imperfections

No special problems exist, only those typically associated with all shear-loaded compression test methods. A rigid post-and-bearing alignment system helps reduce the sensitivity to specimen imperfections.

4. Acceptability of Failure Modes

Failure modes are similar to those observed in other shear-loaded specimen test methods.

5. Simplicity and Adequacy of Data Reduction Procedures

Simple $\sigma = P/A$ stress calculation is necessary. It is easier than with a standard IITRI fixture to use an extensometer rather than a strain gage to measure strains, because of the smaller size of the fixture, and thus the shorter reach distance into the narrow (0.5") gap between the fixture halves.

6. Specimen Preparation and Fixture Requirements

A standard straight-sided, tabbed specimen geometry is used. The standard Wyoming-Modified IITRI fixture accommodates a 5.5" long specimen, although a shorter specimen can be used, the same as for the IITRI fixture. However, the maximum specimen width is typically 0.50".

7. Consistency of Results and Other Information

Test averages and data scatter are similar to those obtained using any of the other compression test methods.

2.2 END-LOADED SPECIMEN TEST FIXTURE CONFIGURATIONS

2.2.1 ASTM D 695 Compression Test Method

1. Problems Associated With Load Introduction and Free Edges

As with any of the direct end-loaded specimen test methods discussed in later sections, end crushing of strong materials is a problem. The standard flat dogboned specimen attempts to minimize the problem by increasing the bearing area at its enlarged ends.

2. Uniformity of the Stress Field

Stress concentrations occur at the radius present in the region where the specimen width is reduced.

3. Sensitivity to Imperfections

As with any of the direct end-loaded specimen test methods, flatness and parallelism of the specimen ends is important so that the loading can be introduced uniformly, to minimize end crushing.

4. Acceptability of Failure Modes

As with dog-boned tensile specimens, at least the majority of specimen failures should occur in the gage section, away from the necked region. For unidirectional composites, premature splitting of the enlarged specimen ends is a common, and unacceptable, failure mode.

5. Simplicity and Adequacy of Data Reduction Procedures

Simple $\sigma = P/A$ stress calculation is needed. The ASTM standard does not provide for the use of strain gages. An extensometer can be mounted on the edge of the specimen

protruding from the lateral supports if it is necessary to measure strains. The standard specimen is 0.50" wide in the gage section.

6. Specimen Preparation and Fixture Requirements

Because of the dog-boned specimen configuration, it is convenient to use a router or similar device to machine the specimen. No tabs are required. The fixturing consists of simple lateral supports, held together against the specimen with screws.

7. Consistency of Results and Other Information

This test method is not commonly used with composite materials, the Modified D 695 test method, incorporating a straight-sided, tabbed specimen, being used instead.

2.2.2 Modified ASTM D 695 Compression Test Method

1. Problems Associated With Load Introduction and Free Edges

As with any of the direct end-loaded specimen test methods discussed in later sections, end crushing of strong materials is a problem. Thus, the straight-sided compressive strength specimen is tabbed, to increase the bearing area.

2. Uniformity of the Stress Field

Stress concentrations exist at the tab ends, but similar to shear-loaded compression specimens, the magnitudes are not well known.

3. Sensitivity to Imperfections

As with any of the direct end-loaded specimen test methods, flatness and parallelism of the specimen ends is important so that the loading can be introduced uniformly, to minimize end crushing.

4. Acceptability of Failure Modes

Failure modes are very similar to those observed in shear-loaded specimens, even though the method of load introduction is quite different. Failures frequently occur at the tab ends.

5. Simplicity and Adequacy of Data Reduction Procedures

Only a simple σ = P/A stress calculation is necessary. A tabbed specimen with only a 0.188" gage length is used to determine strength. This gage length is too short to accommodate a strain gage or extensometer. Thus, a second, untabbed straight-sided specimen is used if modulus is to be determined also.

6. Specimen Preparation and Fixture Requirements

Standard tabbing procedures are used, but with untapered tabs and an uncharacteristically short (0.188") gage length. As for the ASTM standard version, the fixturing for the modified test method is relatively simple. A base has been added, to mount the lateral supports on, and to aid in maintaining loading alignment. A third lateral support with a strain gage clearance cutout is provided also.

7. Consistency of Results and Other Information

Preliminary comparative results indicate that averages and data scatter are very similar to those obtained using any of the shear-loaded specimen test methods, including the IITRI test fixture.

2.2.3 Wyoming End-Loaded, Side-Supported (ELSS) Compression Test Method

1. Problems Associated With Load Introduction and Free Edges

End crushing of untabbed strong composite materials (typically those with compressive strengths greater than about 125 ksi) is a problem. This is a special concern with this test

fixture since it was originally developed with the intention of using a simple untabbed, straight-sided specimen. The fixture itself establishes the gage length (unsupported length) of the specimen. A tabbed specimen can be used for higher strength materials, e.g., a specimen identical to the IITRI configuration.

2. Uniformity of the Stress Field

The lateral supports undoubtedly induce some stress concentration at the ends of the gage length, but similar to shear-loaded compression specimens, the magnitudes of these stress concentrations are not well known.

3. Sensitivity to Imperfections

Flatness and parallelism of the specimen ends is important so that the loading can be introduced uniformly, to minimize end crushing.

4. Acceptability of Failure Modes

Failure modes are very similar to those observed in shear-loaded specimens. End crushing failures will occur at the ends of untabbed specimens when high strength materials are tested, negating the test.

5. Simplicity and Adequacy of Data Reduction Procedures

Only a simple σ = P/A stress calculation is necessary. Because of the adequate gage length (typically 0.50" as in the Celanese and IITRI test methods), strain gages can be mounted on the same specimen used to determine strength, a distinct advantage over the Modified ASTM method. Also, because of the compact nature of the simple fixture, an extensometer can be readily used instead.

6. Specimen Preparation and Fixture Requirements

When no tabbing is required, this straight-sided specimen represents the ultimate in specimen preparation simplicity. As for the ASTM D 695 Standard, the test fixture is also very simple, consisting of four blocks held together in pairs by bolts.

7. Consistency of Results and Other Information

Preliminary comparative results indicate that averages and data scatter are very similar to those obtained using any of the shear-loaded specimen test methods.

2.2.4 RAE (Royal Aircraft Establishment) Compression Test Method

1. Problems Associated With Load Introduction and Free Edges

This test method was developed at the RAE in England in the early 1970's. It has not been used extensively, however. Its two principal features are that the specimen is thickness-tapered (rather than width-tapered as the ASTM Standard D 695 is) and that the untabbed specimen ends are adhesively bonded into close-fitting, relatively deep (0.59" deep) slots in the end-loading fixtures. It is estimated that approximately half of the applied end loading is thus actually induced into the specimen via shear transfer through the adhesive bonds.

2. Uniformity of the Stress Field

The combined end- and shear-loading condition should result in a more favorable load introduction than if one or the other is applied individually. However, the continual thickness tapering will induce some stress concentration. Detailed analysis is required to determine how uniform the stress field is.

3. Sensitivity to Imperfections

Symmetry of specimen machining is one significant source of imperfections, along with misalignments induced when bonding the aluminum end fittings on.

4. Acceptability of Failure Modes

In much of the original work, the specimens buckled rather than failing in compression. Thus, although attractively high strength values were achieved, acceptable failure modes were not obtained.

5. Simplicity and Adequacy of Data Reduction Procedures

Only a simple σ = P/A stress calculation is necessary, using the minimum cross-sectional area of the specimen. However, because of the lack of a constant thickness gage length, it is difficult to monitor specimen strains accurately.

6. Specimen Preparation and Fixture Requirements

The circular arcs forming the reduced thickness must be machined into each face of the specimen. A special test fixture is required, but it is very simple, consisting only of two aluminum blocks, each with a slot machined across one face.

7. Consistency of Results and Other Information

Higher strengths than obtained using the Celanese test method have been reported. However, specimen buckling is still a problem.

2.2.5 Block Compression Test Method

1. Problems Associated With Load Introduction and Free Edges

A common compression test method for homogeneous materials such as metals, and sometimes even brittle materials such as ceramics, is to load a cube or short column of the material between parallel flat platens. This simple approach has long been attempted with composite materials as well, usually with limited success. Just as previously discussed with respect to the ASTM D 695 and ELSS test methods, end crushing is a problem. Thus, extensive studies have been performed in attempts to devise a suitable end reinforcement. Since these block specimens are not laterally supported, except possibly just near each end, buckling is a problem. Thus, an adequately thick composite must be available for testing.

2. Uniformity of the Stress Field

Stress concentrations are induced at the ends of the block specimen, which lead to premature failures. This is true whether the specimens are reinforced or not.

3. Sensitivity to Imperfections

Flatness and parallelism of the specimen ends, and also the loading platens, is critical, since the loading must be introduced uniformly, to minimize end crushing. If end fittings are used, their attachment induces another possible misalignment imperfection.

4. Acceptability of Failure Modes

Failures are usually initiated at the specimen ends, and are thus unacceptable. For this reason, this test method is not commonly used at the present time for compression testing composite materials.

5. Simplicity and Adequacy of Data Reduction Procedures

Only a simple $\sigma = P/A$ stress calculation is necessary. Also, the specimen is typically long enough to permit strain gages or an extensometer to be used.

6. Specimen Preparation and Fixture Requirements

When no end reinforcement is required, the block specimen represents the ultimate in specimen preparation simplicity, and no special fixture is required.

7. Consistency of Results and Other Information

Results are typically very scattered because of the difficulty in controlling the end conditions from one specimen to the next. Thus, this test method is only used in very special cases, e.g., measuring the through-the-thickness compressive strength of a composite laminate.

2.3 SANDWICH LAMINATE SPECIMEN TEST METHODS

2.3.1 ASTM D 3410 Compression Tests, Method C - Sandwich Beam Flexure

1. Problems Associated With Load Introduction and Free Edges

A 22" long, 1" wide, approximately 1.6" deep sandwich beam is subjected to four-point bending. The core material must be sufficiently strong in shear and through-the-thickness compression so that it does not shear fail or crush before the compressive face sheet fails.

2. Uniformity of the Stress Field

The compressive face sheet is thin (typically on the order of 0.030" thick) relative to the overall beam depth. Thus, it is, to a good approximation, in uniform compression. The

maximum bending moment is constant between the loading points. The measured compressive strength is thus affected by any stress concentrations at the loading points.

3. Sensitivity to Imperfections

The test method is very sensitive to any premature failures in the core material or its adhesive bond to the face sheets.

4. Acceptability of Failure Modes

All failures must occur in the compressive face sheet, and a reasonable percentage of these should occur in the central span away from the loading points. Otherwise there is no way of determining the validity of the test.

5. Simplicity and Adequacy of Data Reduction Procedures

The compressive strength is calculated using simple beam theory, neglecting the influence of the core material. Compressive strains are typically measured using a strain gage (the ASTM standard recommends using the average of two gages) bonded to the compressive surface of the beam between the loading points.

6. Specimen Preparation and Fixture Requirements

Although the fixturing can be relatively simple, specimen preparation is not. A capability must exist for fabricating high quality sandwich laminates. Also, a considerable amount of test material is consumed in each specimen.

7. Consistency of Results and Other Information

Data in the literature suggest that the scatter for properly conducted tests is low, at least as good as for any of the other compression test methods. Strength averages tend to be as high, or even slightly higher, than achieved using other methods.

2.3.2 Sandwich Column Axial Loading Compression Test Method

1. Problems Associated With Load Introduction and Free Edges

A sandwich laminate is fabricated, with both face sheets becoming test specimens when the sandwich is loaded on edge as a column in compression. The core is present to permit the face sheets to laterally support each other against buckling. All of the end crushing problems associated with other untabbed, end-loaded specimens exist, however, as previously discussed.

2. Uniformity of the Stress Field

The specimen ends must be reinforced sufficiently so that they do not crush. Some stress concentration will then be induced at the gage length ends of these reinforcements. Thus, at least some failures must occur in the sandwich specimen away from these regions. Otherwise, there is no way of determining validity.

3. Sensitivity to Imperfections

The end reinforcements become potential imperfections. In addition, the core material must not debond from the face sheets.

4. Acceptability of Failure Modes

If end crushing and face sheet debonding are prevented, the failure modes obtained are usually acceptable.

5. Simplicity and Adequacy of Data Reduction Procedures

Only a simple $\sigma = P/A$ stress calculation is necessary, using the combined cross-sectional areas of the two face sheets. Because the outer surfaces of the face sheets are

fully exposed, there is no difficulty in using strain gages or an extensometer to measure the compressive strains.

6. Specimen Preparation and Fixture Requirements

As for the sandwich beam discussed above, a capability must exist for fabricating high quality sandwich laminates. In addition, a suitable end reinforcement scheme must be devised. No special fixture is required, however, the specimen typically being loaded between flat platens.

7. Consistency of Results and Other Information

The test results are extremely dependent upon the quality of specimen and end reinforcement preparation. However, the method is fundamentally capable of giving results consistent with those obtained using any of the other compression test methods.

2.3.3 MINI-SANDWICH COLUMN AXIAL LOADING COMPRESSION TEST METHOD

1. Problems Associated With Load Introduction and Free Edges

This is a recently introduced variation of the Sandwich Column Axial Loading Compression test method discussed above. Rather than using a sandwich laminate with a honeycomb or foam core, the core is a solid, unreinforced polymer, usually the same material as the matrix used in the composite to be compression tested. In work to date, tabs were bonded to the sandwich to form a specimen suitable for testing in the standard IITRI test fixture. Results indicate fewer problems with failures in the tab regions than when testing solid laminates.

2. Uniformity of the Stress Field

Although no analysis has been performed to date, it is possible that the resin core softens the test specimen at the grip/tab ends, reducing the induced stress concentrations. The core material also helps the composite material between tabs resist buckling.

3. Sensitivity to Imperfections

The volume of composite material exposed to the compressive stress is less than in solid laminate specimens, making the presence of material imperfections statistically less.

4. Acceptability of Failure Modes

The available literature suggests that the observed failure mode is compression of individual fibers. Whether this failure mode can be achieved in a solid laminate in a structure has not yet been established. That is, the test method may be forcing a (desirable) failure mode that cannot be achieved in an actual composite structure.

5. Simplicity and Adequacy of Data Reduction Procedures

The compressive stress is calculated from a simple rule of mixtures relation, assuming the core material carries load in proportion to its stiffness.

6. Specimen Preparation and Fixture Requirements

Although a sandwich laminate must be prepared, the fact that the core is unreinforced resin, cocured with the composite face sheets, makes fabrication relatively straightforward. Standard compression test fixtures can be used.

7. Consistency of Results and Other Information

Not enough testing has been performed to date to determine the consistency of results obtained. Preliminary data indicate the attainment of compressive strengths significantly higher (viz., in the range of 25% higher) than those obtained using solid laminates.

2.4 RECOMMENDATIONS

2.4.1 Experimental Work

One of the principal difficulties at the present time is that no one compression test method is generally favored by the composite materials testing community. It has not been clearly established whether the various competing methods can produce similar test averages and standard deviations, and how relatively reproducible and forgiving each method is. It is not known, for example, whether there is any advantage of shear-loaded specimens over end-loaded specimens, or vice versa. It is generally agreed, however, that none of the available test methods is without faults. Thus, an in-depth experimental comparison of the most promising of the available compression test methods needs to be performed. Limited attempts to do this to date, as identified in this report, have suggested that if performed properly, and resulting in proper failure modes, any of the commonly used test methods will provide similar results. Even if this is true, some methods are obviously easier to use, easier to prepare specimens for, and are more tolerant of fixture, specimen, and procedural errors. In performing such a comparative study, extreme care should be taken to obtain the best possible results, to provide a fair comparison. Thus, this comparison study should all be performed by one or a very few of the more experienced testing laboratories, rather than as a broad round robin as is typically conducted by ASTM.

Since this may not be representative of the testing skill level of the industry as a whole, sensitivity studies should then be performed, to determine how tolerant the various methods are to anomalies that are likely to occur. Such anomalies include the influence of tabs or adhesive bond lines of unequal thickness (resulting in loading eccentricities), fiber misalignment, nonuniform thickness along a tab, fixture fabrication inaccuracies, specimen machining errors, inaccurate specimen installation in the fixture, specimen/fixture/testing machine

misalignments, etc. Such a sensitivity study may, in fact, be the principal factor in establishing a generally accepted standard.

Along with rating the various test methods, it remains to establish optimum sizes and configurations of test specimens. For example, it is not generally established what specimen width should be used, or how long the tabs should be for proper loading. The best type of tabbing material to use, and its orientation relative to the test specimen if it is not isotropic, is not yet established. There is much conflicting information in the current technical literature.

Because no one of the existing compression test methods is generally accepted as superior, it may be appropriate to search for a new approach, or a significant modification of one of the existing methods. For example, both shear-loaded and end-loaded specimens have been used extensively. Yet, relatively little study has been devoted to combined shear- and end-loading, as discussed in this report. Such an approach, possibly used in combination with ceramic-particle-coated grip faces (which can be relatively smooth compared to serrated grip faces), could even permit the use of untabbed or unbonded tab specimens.

Correspondingly, the relative performance of these smooth grip faces even when conducting current standard tests, is not known. This in itself requires a specific study.

Along with combined shear- and end-loading, thickness tapering of the test coupon should be examined more closely. While not totally successful in the limited studies conducted to date, and not generally considered a popular approach by the composite materials community, it may be a necessary procedure. By co-curing extra layers of material directly onto the surfaces of the composite to be tested, and then machining through these supplemental layers in preparing the test specimen, some of the current concerns might be reduced. Certainly, width tapering has been generally shown to not be successful. Here again, even a combination of face and width tapering may be necessary, although not very attractive from a specimen preparation viewpoint.

As discussed in this report, preliminary results obtained using the recently developed mini-sandwich axial compression test method suggest that it may be forcing the individual fibers to fail in true axial compression rather than via fiber microbuckling. Very thin face sheets of unidirectional composite are co-cured onto a core layer of neat (unreinforced) matrix material, typically the same type of material being used as the matrix in the composite being tested. Composite compressive strengths obtained in the limited work performed to date have in some cases been significantly higher than those obtained using standard test methods. One

issue then is whether this is a failure mode obtainable in an actual structure, even if it can be obtained in the materials testing laboratory. This is obviously a significant issue since it is often considered that the higher the material property obtained, the better the test method.

This leads directly into the issue of cross-ply versus unidirectional composite testing for obtaining the compressive (and also tensile) strength of the unidirectional ply material. Since a portion of the plies in the composite are not oriented in the loading direction, the applied forces required to fail the cross-ply specimen are lower, making the testing easier to perform. However, an analysis must then be used to back out the unidirectional ply strength. Perhaps the mini-sandwich axial compression test method has some commonality with cross-ply testing. That is, in both cases the test method may be forcing the fibers to fail in an alternate mode. In the case of cross-ply testing, this may not be unattractive if that is the failure mode prevalent in an actual laminate. However, the mini-sandwich axial compression test results suggest that perhaps if a thicker and thicker core of 90° plies were used with very thin 0° plies on the laminate surface (or even buried within the laminate), that higher and higher calculated unidirectional ply compressive strengths would be obtained. Again, this issue appears to be worthy of investigation.

These then are just a few of the many experimental questions remaining to be answered relative to compression testing of composite materials.

2.4.2 Failure Mode Analysis

A statement was made in the above discussion that it is necessary to obtain a valid failure mode. Yet, what constitutes a valid failure mode is not adequately defined at the present time. Studies indicate that changes in failure mode can be very subtle. Thus, it is often not very obvious whether a valid failure mode has in fact been obtained. Since failures occur on both the micro and macro levels, they need to be further studied on both levels, in an attempt to correlate observed characteristic failures with measured compressive strengths.

2.4.3 Analytical Studies

Experimental work is typically very time consuming and expensive. Thus, it must usually be limited in scope. Also, many properties of a composite material cannot be readily

characterized experimentally. With the continued development and refinement of mathematical analyses, particularly finite element analyses, it is now possible to predict the response of the composite to the many parametric variables that potentially exist. Only the more significant of these then need to be verified experimentally. That is, the use of a combined analytical/experimental study can be much more efficient that a purely experimental characterization.

Problems readily amenable to mathematical analysis include the influence of type of tabbing material and configuration, wedge grip force, nonuniform end load distribution effects, specimen-grip interactions, and fixture loading irregularities. Also, most of the problems discussed above with respect to experimental studies can also be concurrently, or preferably preliminarily, studied analytically. In particular, this includes the variation in the stress distribution in the test specimen as a function of the thickness tapering geometry, and the influence of combined shear- and end-loading.

3. DETAILED DISCUSSION OF THE VARIOUS COMPRESSION TEST METHODS

Each of the compression test methods summarized in the previous section in terms of the seven specific categories indicated will now be discussed in more detail. The detailed discussion of each will follow the same general outline, i.e., GENERAL DESCRIPTION OF THE TEST METHOD, STRESS STATES AND FAILURE MODES, and OTHER REQUIREMENTS AND MODIFICATIONS.

3.1 SHEAR-LOADED COMPRESSION TEST SPECIMENS

3.1.1 Celanese Compression Test Method

General Description of the Test Method

This was the first of the shear-loaded compression test methods to be standardized by ASTM, as ASTM Standard D 3410, in 1975 [1]. It was developed by I.K. Park at the *Celanese Corporation*, being published in the open literature in 1971 [2], and also being publicized in company literature with encouragement for the composites community to try it [3]. In fact, an offer was made to loan a fixture to any potential user, or to provide them with a set of blueprints so they could machine their own, or arrange to have one made for them. That is, Celanese strongly promoted the new test method. Hence the name Celanese compression test method soon became used to identify it.

Until 1987, when the IITRI and Sandwich Beam Flexure compression test methods were added to the same standard, as Methods B and C, respectively, the Celanese compression test remained as the only standardized compression test method of this type.

A general schematic drawing of the test fixture is shown in Figure 1. Photographs of an actual fixture as defined in the ASTM standard are shown in Figure 2.

The fixture incorporates specimen grips each consisting of a split truncated circular cone that fits inside a truncated circular cone-shaped cavity in a mating holder. This requires the tabbed specimen, which is sandwiched between the split cones, to be of a precise thickness if the assembled split cone is to seat perfectly in the cone-shaped cavity. However, the tabbed specimen itself is compressed as the grips tighten via the wedging action as the axial

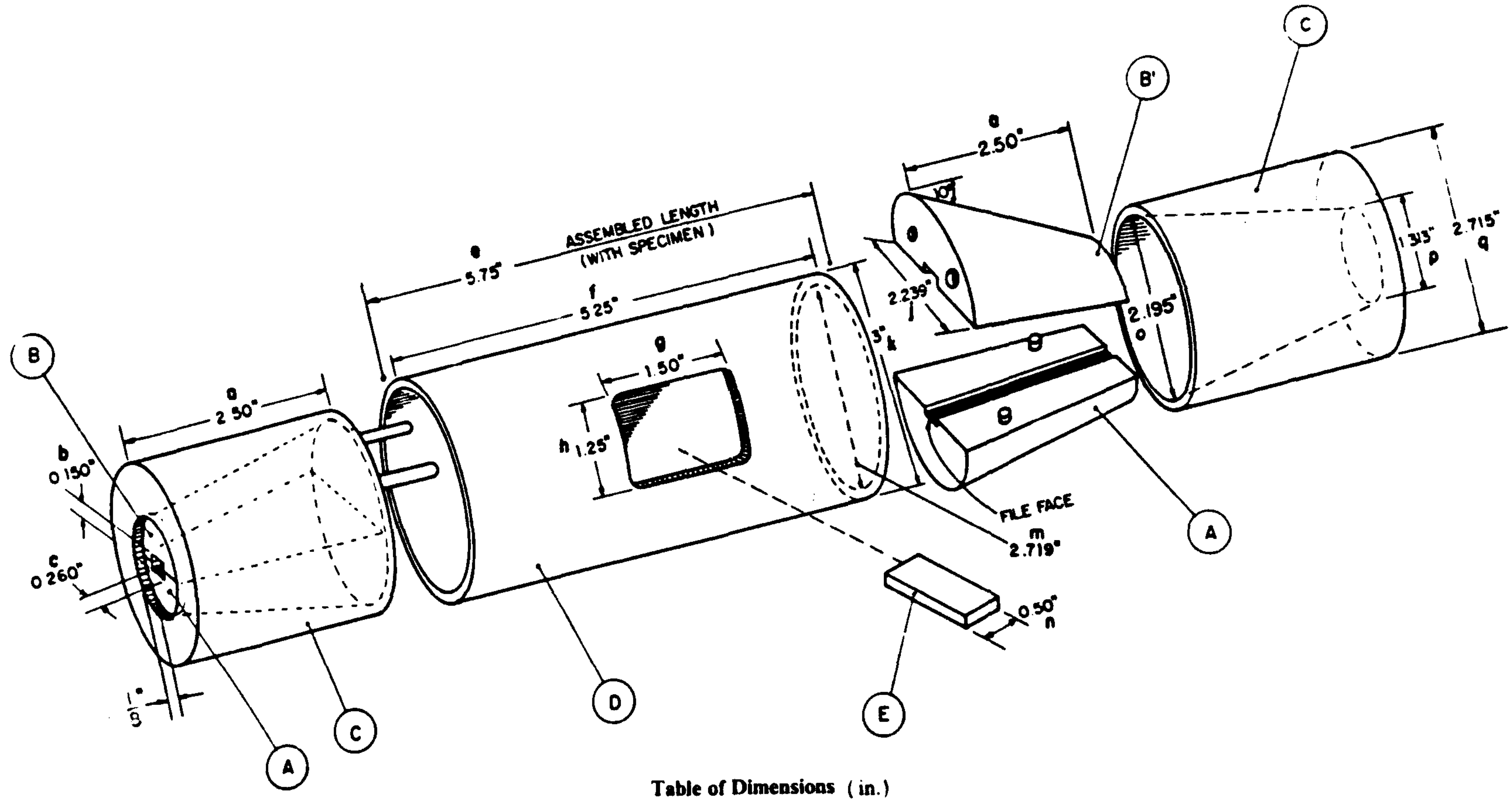
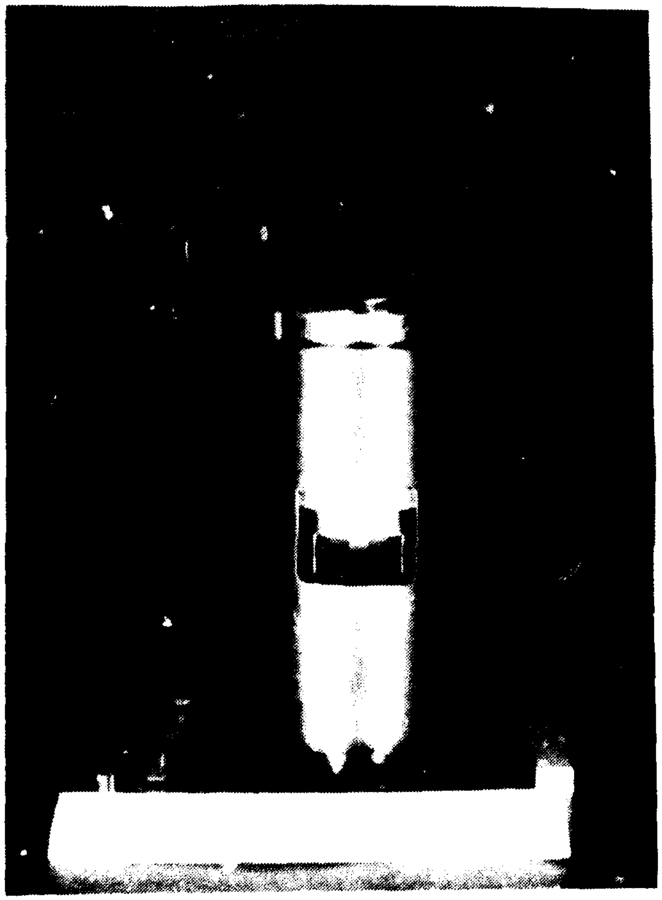


Table of Dimensions (in.)

	Dimension		Dimension
a	2.500	j	2.239
b	0.150	k	3.000
c	0.260	m	2.719
d	0.125	n	0.500
e	5.75	o	2.195
f	5.25	p	1.313
g	1.50	q	2.715
h	1.25		

Figure 1. Celanese Compression Test Fixture [1]



Assembled Fixture

Fixture Components

Figure 2. Celanese Compression Test Fixture [9]

compressive loading is applied to the fixture. That is, the effective thickness of the tabbed specimen continually changes as the load is applied. The amount of specimen/tab compression depends upon the type of material being tested and the type of tabbing material being used. However, dimensional changes on the order of 0.005" are typical. This is a significant magnitude when it is considered that the ASTM Standard D 3410 [1] specifies a specimen/tab thickness of 0.157" ± 0.002". That is, the variable compression due to gripping is on the order of 2½ times the specimen tolerance.

After manually closing the grips with the tabbed specimen inside, the grips are fitted into the conical cavities of the fixture with a spacer bar placed between the top and bottom grips. This assembly is then placed inside the cylindrical sleeve. The fixture is preloaded before the spacer bar is removed.

The fixture is actually designed so that the gap between the split cones when no specimen is present is nominally 0.150". The allowable machining tolerances, per the ASTM fixture drawings, allow this gap to vary only from 0.149" to 0.151". However, even this small variation, combined with the specimen tolerance and the variable specimen/tab compression, will result in a noncircular split cone assembly, which then does not seat properly in the circular cone holder. This permits the gripped ends of the specimen to rock (rotate) in the grips, making it easier for the specimen to bend and/or buckle, which is fatal in a compression test.

It was precisely because of this problem that alternative designs were developed, e.g., the IITRI and the Wyoming-Modified Celanese compression test fixtures as two significant examples, both of which will be discussed in detail subsequently. It is interesting that Adsit [4] makes the comment that "what is commonly called the IITRI method was originally examined by Celanese investigators at the same time that the conical shaped wedge fixture was being developed." No reference is made to flat wedge faces in Park's paper introducing the Celanese Compression Test Method [2], nor in the Celanese literature at the time [3].

The inherent design problem of using conical wedges has long made data generated using the Celanese compression test method questionable even though, as noted above, until 1987 it was the only standardized compression test method available intended specifically for composite materials. In fact, literature data [4] would suggest that if the test is conducted properly, the results obtained, in terms of both compressive strength and modulus averages,

and scatter of the data, differ little from the other, more readily accepted methods, in particular the IITRI compression test method.

The ASTM Standard D 3410 Celanese test specimen is 5.5" long, with 2.5" long tabs bonded to each end to form a 0.50" gage length (untabbed length of specimen) in the center. Interestingly, even though the original Celanese fixture had grips 2.5" long, the specimen was only 4.5" long, with 2" tabs on each end [2,3]. Presumably the specimen tabs were lengthened when the Celanese design was adopted as an ASTM Standard.

The tabs are usually tapered at the inner ends (at the gage section) to reduce stress concentrations. However, untapered tabs can also be used. While the original Celanese specimen tabs were tapered, the taper angle appears to have been on the order of 45° [2], i.e., a very short taper length about equal to the thickness of the tabs, viz., 0.050". The ASTM Standard D 3410 defines a much longer taper length, equal to the specimen width, i.e., 0.250", which is five times longer.

Various types of tabbing material are used, with glass-fabric/epoxy now having been the most popular choice for a number of years. This material is readily available at relatively low cost as it is typically manufactured in large quantities for use as printed circuit boards. The ASTM standard recommends (it will be noted that it does not require) the use of glass/epoxy cross-ply composite tabs, i.e., a composite fabricated of unidirectional plies of glass fiber-reinforced epoxy, with the fibers in the surface layer oriented parallel to the axis of the test specimen. There have been a number of reports of the tabs shearing off internally between layers when cross-ply glass/epoxy laminate tabs have been used. When glass-fabric/epoxy tabs were substituted the problem was solved. For example, one such case was reported recently by Lubowinski [5]. Similar difficulties have been encountered when using cross-ply carbon/epoxy tabbing materials [6]. The justification for trying carbon/epoxy was to more closely match the stiffness of the carbon/epoxy composite being tested, as is often suggested be done. However, as will be noted below relative to the use of steel tabs, this does not appear to be a critical requirement, even though frequently mentioned in the literature as being so. An additional problem with using a tabbing material such as carbon/epoxy, in either cross-ply or woven fiber forms, is that the brittle fiber is readily damaged by the aggressive serrated grip faces usually used with many shear-loaded compression test fixtures, causing the surface layers of the tab to strip off of the specimen prematurely. The file faces of the Celanese fixture are not as aggressive as serrated faces,

and thus the problem is not quite as severe. However, because of the very forgiving nature of glass-fabric/epoxy tabs with respect to grip surface damage, there appears to be little reason to use anything else at the present time. For example, in successful tests of very strong composite materials using a fixture such as the IITRI, with serrated grip faces, the failed test specimen will typically exhibit tabs which are "well chewed up". In fact, however, the deep penetration of the serrated grips provided the very high holding power required.

In earlier years the use of aluminum tabs was common, but they are seldom used now in the United States, although sometimes still being used in Europe. Steel tabs (low carbon steel so that the fixture grips can dig into the tabs and seat properly) are recommended in the ASTM standard for use when testing "high modulus" composite materials, i.e., composites having moduli greater than 10 Msi. However, this recommendation is seldom followed, probably because it is much more difficult to work with steel tabs. They do not bond to the polymer-matrix composite as well as polymer-matrix tabs, and they are more difficult to machine when bonded onto the composite. In fact, recent research [7] has shown that there is very little difference in measured compressive strengths for high modulus composites such as unidirectionally-reinforced carbon/epoxy when glass-fabric/epoxy tabs are used rather than steel tabs. Additional discussion of tab configurations and materials is presented by Hart-Smith [8].

It should be noted that the preferred way of putting tabs on compression specimens (and tensile specimens also) is to bond plates of the tabbing material (typically 1/16" thick since this is a standard, readily available thickness) across both ends, on both sides, of a plate of the composite that individual test specimens are to be made from. If the tabs are to be tapered, they are machined to the desired taper angle before being bonded in place. Often a special jig (e.g., see Reference [9]) is used to hold the four pieces of tabbing material in their proper positions on the composite plate while the adhesive is curing, as the assembly is very "slippery" until the adhesive sets. After the adhesive is properly cured, the assembly is sliced into individual specimens, perhaps using a slitting saw or similar circular-blade cutting device. This tabbing procedure is detailed here since surprisingly it was not "discovered" by the composites community as a whole until about 1975. Before then it was common to cut the composite into individual strips and then to adhesively bond four precut tabs onto each specimen. Not only was this a tedious, time consuming procedure, it resulted in considerable variation from specimen to specimen.

The standard Celanese specimen is only 0.25" wide, with the standard fixture (as shown in Figures 1 and 2) being designed to accommodate a specimen no wider than this. Of course there is no reason why a fixture could not be fabricated to accommodate a wider specimen, and in fact this has been done, with no difficulty [9]. While a 0.25" wide specimen is probably adequate in most cases, such a narrow specimen does emphasize any influences of material or fabrication imperfections, such as fiber misalignments and cutting damage at the free edges. While there is no "standard" compression specimen width, it has become very common to use a 0.50" wide specimen with other fixture designs, as will be noted subsequently.

Stress States and Failure Modes

All of the compression test methods relying on shear to transfer the load from the testing machine through fixture grips into the specimen, typically via tabs, present a similar problem. That is, there is a stress concentration in the test specimen due to the discontinuity in the region at the end of the gage length where the tab begins. Tabs are used, of course, to protect the composite material itself from damage by the grip faces. Although relatively aggressive serrated grip faces are commonly used with other shear-loaded compression specimen fixtures, the Celanese fixture as defined by ASTM [1] incorporates less aggressive file face inserts. That is, 0.50" wide rectangular pieces with rounded ends cut from an actual metal-working file are inserted in cutouts in the split-cone grips. These file faces usually do hold adequately, even when testing strong composite materials. Recently, ceramic particle-coated grip faces have begun to be used also, tungsten carbide particles in a metal binder being the most common [9]. These are often referred to as "flame-sprayed" coatings, but various other processes are actually also used. Even relatively smooth surfaces appear to hold well [6], although no detailed experimental investigation has yet been performed to determine the optimum roughness.

The discontinuities at the ends of the tabs, combined with the large clamping forces induced by the steel wedge grips, which are also relatively stiff, induce stress concentrations in the composite material being tested, although their magnitude has not yet been adequately determined, as will be discussed in detail in the DETAILED REVIEW OF ANALYTICAL STUDIES section of this report. Since all of the other shear-loaded compression test methods, e.g., the

Wyoming-Modified Celanese, IITRI, and Wyoming-Modified IITRI test fixtures, undoubtedly suffer the same magnitudes of stress concentrations, and thus produce measured strengths also degraded to about the same extent, no one method can be used as a standard of comparison to evaluate the others. It appears that only a rigorous stress analysis will be able to quantify the loss in measured strength due to the induced stress concentration. At present, such an analysis does not exist.

It does appear, however, that whatever stress concentration is present at the tab ends, it does not extend very far into the gage section. Experimental studies of the influence of gage length, on both shear-loaded and end-loaded compression specimens, indicate little influence of gage length [10]. If the stress concentration did extend a significant distance into the gage section, then it would be expected that for short gage sections the stress fields extending into the gage section from each end would overlap, increasing the magnitude of the stress concentration. Thus, as the gage length became shorter and shorter, the measured compressive strength would decrease. This has not been generally observed experimentally [10], although early works [11] suggested that it might be.

In fact, available analyses [12-14] do appear to support this somewhat surprising experimental observation. The predictions are that the stress concentrations may extend no more than 0.050" to 0.100" into the gage section.

Because of the stress concentrations present at the tab ends, failures commonly occur at, or even slightly inside the tabs [15]. While not considered "acceptable," such failures are currently usually accepted anyway simply because it is not known how to avoid them. Again it appears that careful mathematical analyses are needed as an aid in determining what can be done to minimize these stress concentrations. Acceptable failures of Celanese compression test specimens are shown in Figure 3, these being obtained when testing relatively low strength sheet molding compound composites [6]. Limited experimental studies to date of the influences of type of tab material, gripping condition, and tab taper, have suggested that these factors have relatively little influence on the measured compressive strength, as is indicated in the data of Table 2 [7]. The gripping conditions and tab taper are defined in Figure 4. Premature tab debonding during a test is sometimes also a concern [7]. As indicated in Table 3, this does not appear to be a serious problem. The specimens were deliberately left unbonded over the lengths indicated during specimen fabrication, with minimal influence being noted when compression tested [7].

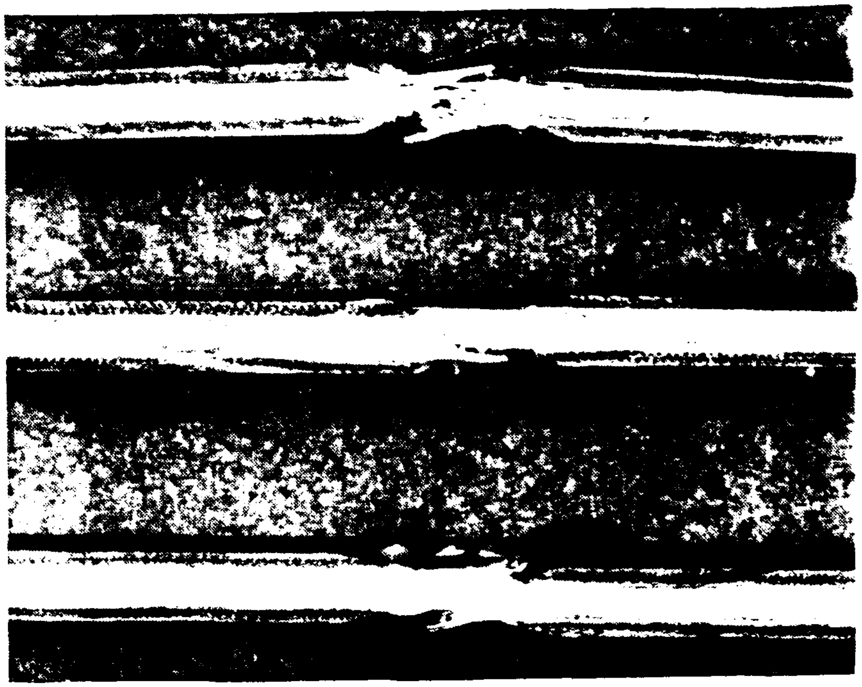


Figure 3. Typical Failures of Celanese Compression Test Specimens of Randomly Oriented, Short Glass Fiber/Epoxy Composites [6]

There is much controversy at present as to what the proper compressive failure mode should be. Although excellent discussions are presented in several references (see, for example, [7,10,15-20]), experimental observations are not very conclusive. In general, the failure modes exhibited by Celanese specimens appear to be little different from those produced by any of the other compression test methods.

As for all of the other shear-loaded and end-loaded compression test methods, the compressive stress is simply the applied force at failure divided by the cross-sectional area of the gage section of the specimen, i.e., $\sigma = P/A$.

When using the Celanese compression test fixture, it is intended that a strain gage be used if the compressive modulus is to be determined. The constrained space and the presence of the alignment sleeve makes it difficult to use an extensometer, although it can be done. For example, the sleeve can be slotted from one central cutout to one end, as shown in Figure 5. Then the extensometer can be mounted on the specimen before it is installed in the test fixture. The cutout permits the sleeve to be slid down past the protruding extensometer body. This cutout does significantly reduce the effectiveness of the sleeve, but

Table 2. Compressive Strength of an AS4/3501-6 Carbon/Epoxy Unidirectional Composite Material as a Function of Tab Material, Tab Taper, and Gripping Conditions [7]

Type of Tab Material	Taper	Gripping Condition	Strength (ksi)	
			Average	Std. Dev.
Plate 1 (V_F = 70%, V_V = 0.8%, Average of 5 Specimens Each)				
Steel	No	Flush	226	10
Steel	No	Extended	224	15
Steel	Yes	Flush	232	12
Glass	Yes	Flush	192	20
Plate 2 (V_F = 67%, V_V = 1.3%, Average of 9 Specimens Each)				
Steel	No	Flush	246	17
Steel	Yes	Flush	255	16
Glass	No	Flush	243	15
Glass	Yes	Flush	203	3

it is actually more of an "indicator of misalignment" rather than an alignment restraint anyway, in spite of its original intended purpose. That is, the sleeve, although close fitting, must remain free to move relative to the grip blocks it surrounds. Otherwise an unknown portion of the compressive load applied by the testing machine could be transmitted through this sleeve, making the test specimen material appear to be stronger (and stiffer) than it actually is. As discussed in the ASTM Standard [1], it is necessary to periodically check the sleeve while a test is in progress, by sliding it up and down by hand to make sure it is not binding. If it is not binding, this means of course that it is serving no function at that time. If it does bind, it is because it is resisting misalignments beginning to be induced, and frictional forces are being developed between the sleeve and the grip blocks. But, as noted above, these frictional forces, which are carrying a portion of the applied loading through the

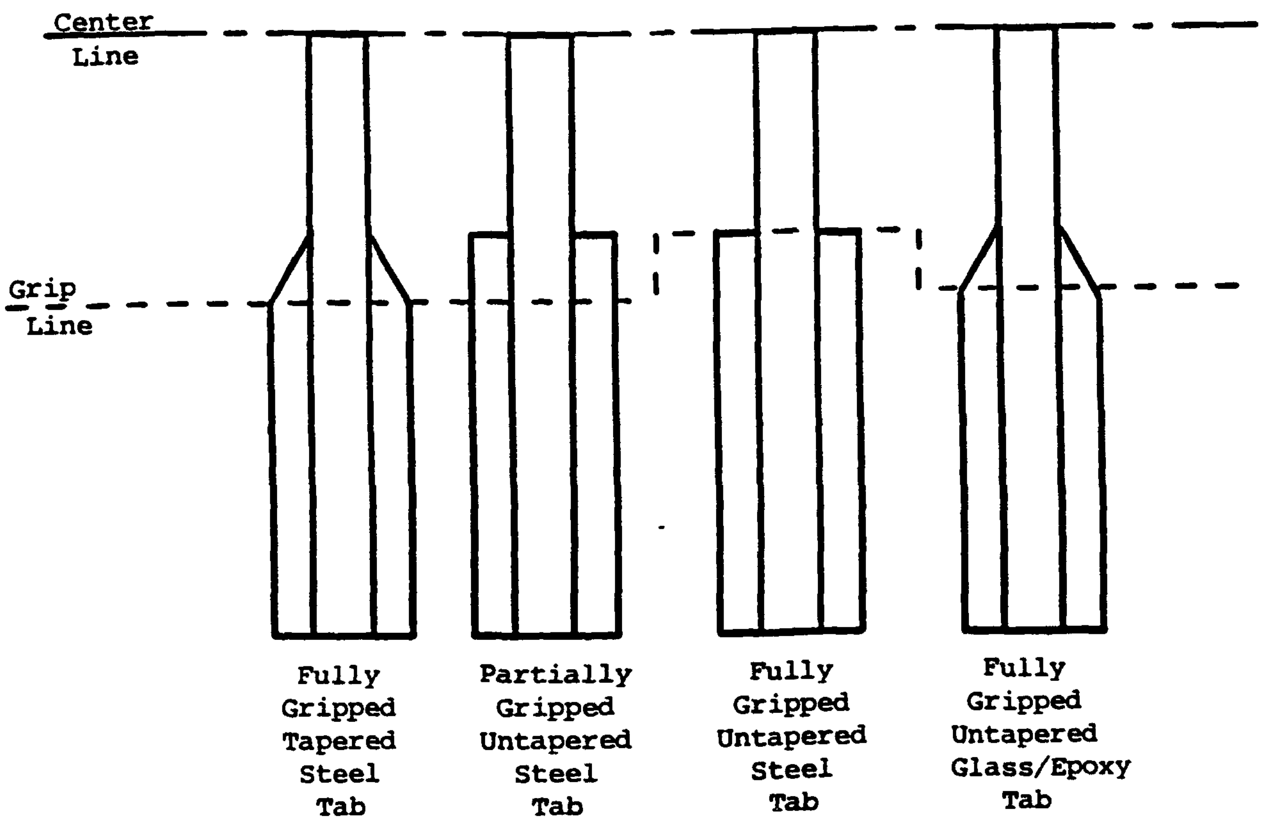


Figure 4. Side View Sketches of Specimen Tabbed Ends, Indicating Tab Matrial, Tab Taper, and Gripping Conditions [7]

Table 3. Compressive Strength of an AS4/3501-6 Carbon/Epoxy Unidirectional Composite Material as a Function of Deliberate Debonding of the Tabs [7]

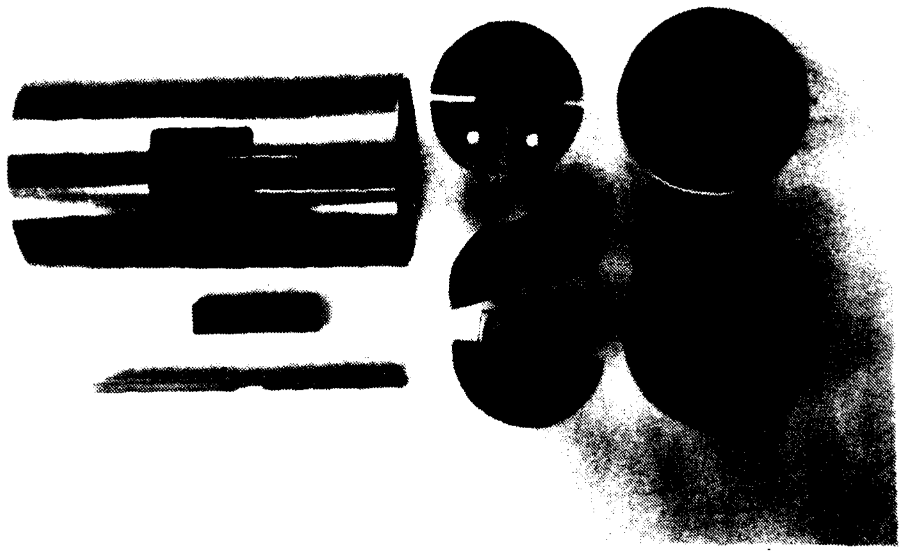
Untapered Glass Fabric Tabs, IITRI Test Fixture
(All Specimens Cut From Same Composite Plate)

(V_F = 67%, V_V = 1.2%)

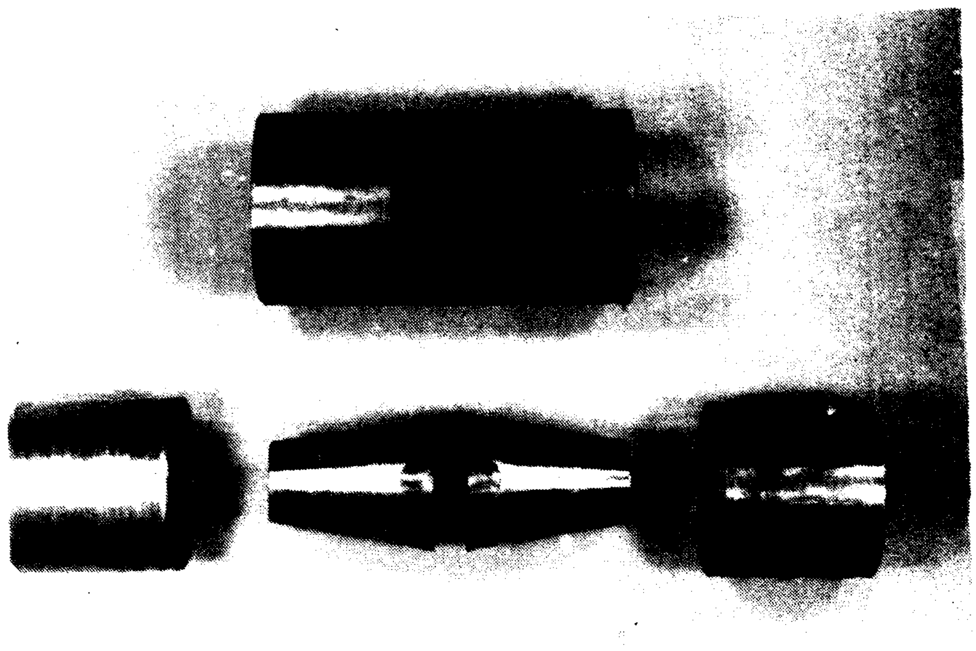
Extent of Tab Debonding	No. of Specimens	Compressive Strength (ksi)	
		Average	Std. Dev.
No Debond	8	236	15
¼" Debond	7	229	9
½" Debond	7	220	22
(Tapered Steel Tabs, No Debonding)	8	242	9

sleeve rather than through the test specimen, are totally unacceptable. Thus, the sleeve can never be used to maintain alignment, but only as an indicator of misalignment. If a frictionless sleeve were available, of course, this would solve the problem. This is exactly the approach of the competing compression test fixtures such as the Wyoming-Modified Celanese, the IITRI, and the Wyoming-Modified IITRI, which replace the "alignment" sleeve with a post and ball bushing arrangement, which exhibits very low frictional forces and is essentially impossible to bind up.

As with any compression test, whenever there is any concern about specimen bending or buckling, it is necessary to use instrumentation on both of the surfaces of the specimen that are outboard from the minimum moment of inertia axis. For a specimen of rectangular cross section such as the Celanese, these are the 0.25" wide surfaces. While in theory two



Top View of Grips



Side View of Grips Assembled

Figure 5. Celanese Test Fixture with Alignment Sleeve Slotted to Accommodate an Extensometer [9]

axial extensometers could be used, it is perhaps more practical, and certainly almost universally common, to use two axial strain gages instead. If bending is present, the two gage readings will diverge from the beginning of the test, such as indicated in Figure 6. In fact, by monitoring the two gage readings at the initial low load levels, if bending is detected the load can be removed, the misalignment corrected, and the specimen then reloaded to failure.

If buckling occurs, it cannot be anticipated experimentally. The strain measuring devices can track each other perfectly up to very high applied stress levels, and then suddenly diverge, as shown in Figure 7. The gage on the convex side of the buckled specimen will be relieved of some of its compressive stress and thus the corresponding axial strain will abruptly decrease. The gage on the concave side of the specimen will correspondingly indicate an equally abrupt increase in axial strain. Thus, the occurrence of buckling is obvious. Unfortunately, the compression test is invalidated.

Buckling is independent of the strength of the material, being dependent on the specimen geometry and the material stiffness. Thus, when buckling has occurred, all that has been determined with respect to the compressive strength of the material is that it is higher than the stress at which buckling occurred. There is no indication as to how much higher. Guidelines for selecting a proper specimen thickness for a given composite material to avoid buckling are given in the Appendix of ASTM Standard D 3410 [1], and have been found to be generally reliable [10].

When a strain measuring device is used, a complete axial stress - axial strain curve to failure can be obtained. It is important to record and preserve this information as it is often very useful for both design and analysis purposes. This becomes a conflict when extensometers are used, as these items are expensive (on the order of $2,000 each), and they may be damaged or destroyed when the explosive compressive failure typical of many types of composite material occurs. When strain gages are used this is not a problem since these thin foil gages are adhesively bonded onto the specimen and are intended to be expendable items, being used only once anyway.

Because of the constrained space and short gage length of most compression test fixtures, including the Celanese, it is common to not measure the lateral strain in the specimen. That is, Poisson's ratio is not determined. It is then usually assumed that the Poisson's ratio in compression is similar to that measured under a tensile loading. While

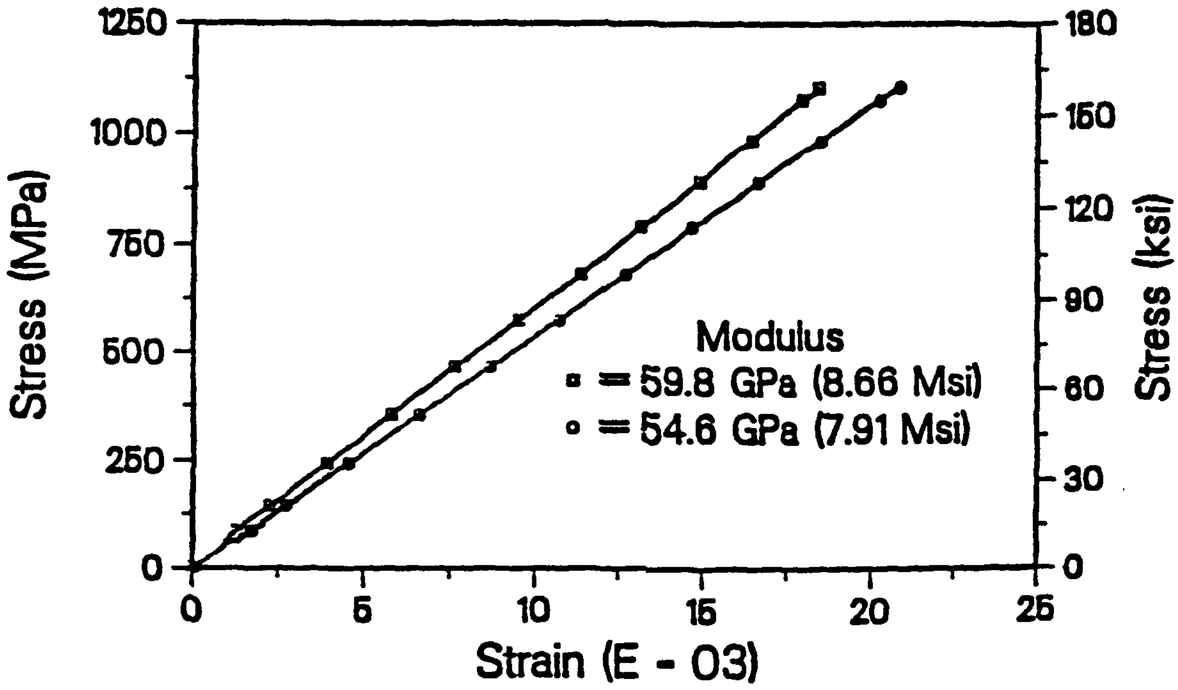


Figure 6. Initially Diverging Strain Gage Readings Indicating Induced Bending (16-Ply Unidirectional S2 Glass/3501-6 Epoxy Composite) [25]

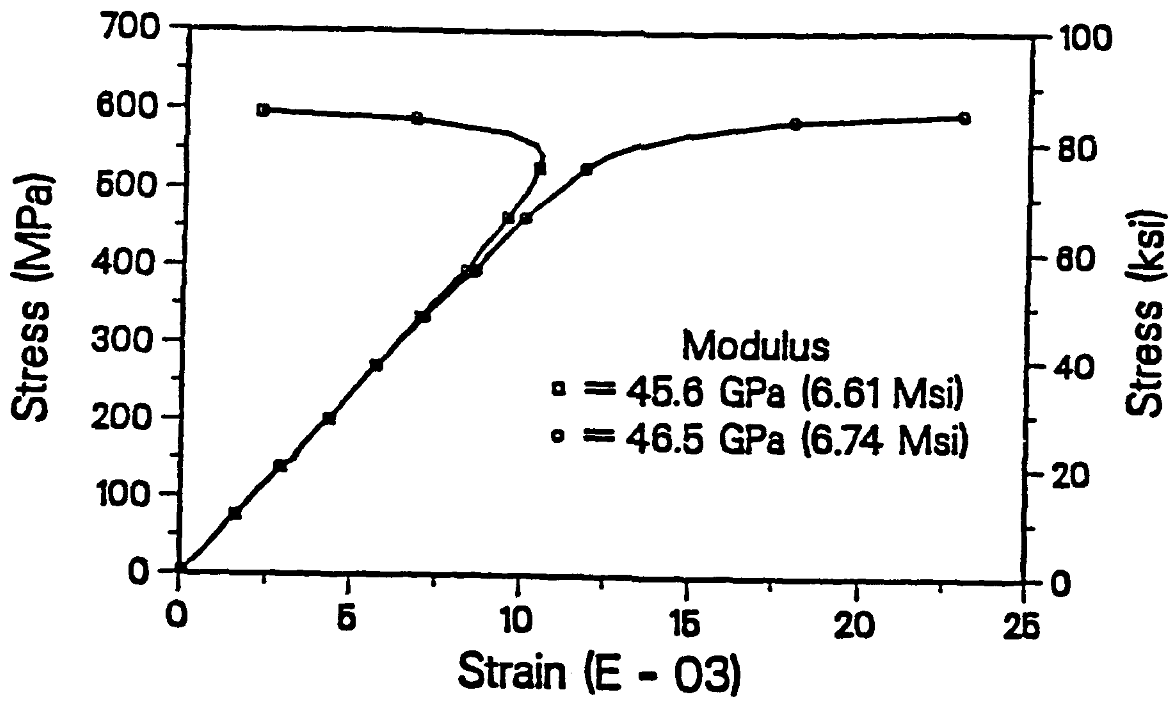


Figure 7. Suddenly Diverging Strain Gage Readings Indicating Buckling (32-Ply Unidirectional S2 Glass/3501-6 Epoxy Composite) [25]

tensile and compressive stiffness properties in general, including both modulus and Poisson's ratio, do not typically differ significantly, this assumption, if made, should be checked whenever uncertainty exists.

Other Requirements and Modifications

A valid criticism of the Celanese compression test method is that the test specimen must be of a very precise thickness at the tabbed ends. Since the stated tolerance in ASTM Standard D 3410 is only ±0.002", and the composite panel and each of the tabs can easily vary in thickness by that amount, combined with the variation in thickness of both of the adhesive bond lines, it is essentially impossible to tab a specimen to this precise thickness (0.157") and tolerance (±0.002"). The tabs must then be machined (typically ground) to the required final thickness. In addition to the extra expense involved, this machining operation can be an additional source of imperfection error. For example, more material may be machined from one tab than the other, introducing a nonsymmetry into the specimen, which can induce both bending and buckling. Correspondingly, the tab surfaces may not be ground parallel to the specimen itself.

Another important limitation is that the composite material to be compression tested must be within a relatively narrow range of thicknesses, since the tabbing materials and adhesives typically available are of standard thicknesses and the total assembly must be 0.157" ± 0.002" thick.

It has been found that the precision of the fixture is also very critical to the success of the Celanese compression test method [5,9]. As discussed previously, the split cone grips must fit very precisely into their mating conical cavities. Obviously this cannot occur unless the individual components are very accurately machined.

Precise alignment between one grip and the other is also not well maintained by the Celanese fixture design. Only two short, small diameter pins are present for this purpose, as shown in Figure 1. And while the outer sleeve is a good indicator that misalignment is present, it cannot be used to force or maintain alignment, as discussed previously. Thus, the machining precision of both the fixture and the specimen, and also the parallelism of the loading platens, is critical. While this required precision can be readily achieved with proper care, the Celanese compression test method is not very forgiving if it is not.

Because of all the potential problems summarized above, results reported in the literature for the Celanese compression test are extremely inconsistent. If the alignment sleeve binds up and thus carries a portion of the applied load, the indicated compressive strength (and modulus) will be artificially high [21]. If the cone wedge grips do not seat properly and can pivot, premature bending or buckling failures can occur, resulting in indicated compressive strengths that are too low [21,22]. The corresponding compressive modulus may be either too high or too low, depending upon which surface of the specimen the strain indicator is mounted on, if only one indicator is used. (If two indicators are used, and the strain signals are averaged, the calculated modulus should be satisfactory.)

In summary, although it is possible to measure compressive strength and modulus just as accurately with the Celanese compression test method as with any competing method [4], the Celanese method is not very forgiving [5,6,21,22]. This makes it much less attractive to use than some of the other methods to be discussed [23,24]. As a result, other shear-loaded compression test fixtures have since been developed, to eliminate or at least minimize these deficiencies [21,22,25-27].

There are, in fact, several direct modifications of the Celanese configuration, one of which is Deutsches Institut fur Normung (DIN) Standard 29 971 [28]. This German standard, published in 1983, modifies the Celanese fixture by replacing the conical wedge grips with flat wedges, as shown in Figure 8. Although the various dimensions are modified slightly, it is otherwise very similar, including the retention of the general circular shape and the use of an alignment sleeve. Certainly the use of flat wedges is a constructive step. No reported uses of this fixture in the United States have been found. Its use in Germany is described by Henrat [29]. He also performed experiments using three different intermediate modulus carbon fibers (Enka Tenax IM 400, IM 500, and IM 600) combined with three different epoxy matrices and a modified bismaleimide matrix, in unidirectional composite forms. He compared the German-modified Celanese fixture with a standard ASTM D 695 fixture [30], but with modified specimens. Compressive modulus values were essentially the same (using a straight-sided, untabbed specimen for the ASTM D 695 testing), but the compressive strengths obtained were consistently 15 to 20 percent lower for the ASTM D 695 testing (using a straight-sided, tabbed specimen with a 5 mm, i.e., 3/16", gage length for the ASTM D 695 testing). He attributed the lower strength to end crushing of the specimens, which could have been caused by either inadequate tab thickness or material type (he did not describe either),

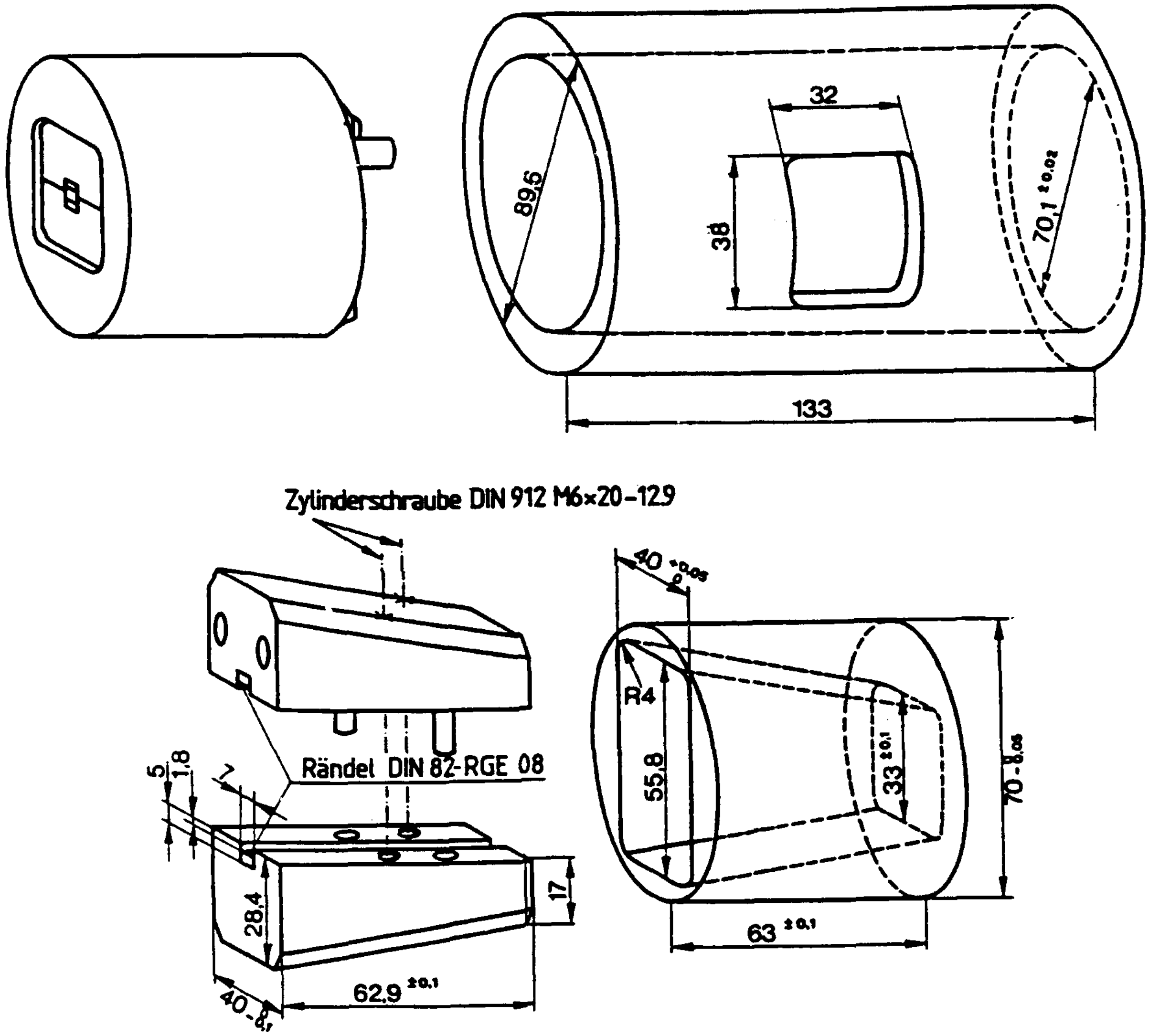


Figure 8. German Standard DIN 29 971 Modification of Celanese Compression Test Fixture [28]

or by inadequate alignment of the fixture in the testing machine. It will be noted that the standard ASTM D 695 fixture [30] used consists of two lateral anti-buckling restraints bolted together with the test specimen sandwiched in between. That is, the fixture itself does not force the specimen to be perpendicular to the loading platens. The strengths obtained using the modified Celanese compression test fixture were about 1500 MPa (218 ksi), which is quite respectable for the materials tested.

An additional modification of the German-modified Celanese compression test fixture is discussed in another paper, by German authors Vilsmeier, et al. [31]. This modification is in the shape of the flat wedge grips. Although data are presented for several different composite material systems, there are no direct comparisons with the German standard or other test fixtures, to demonstrate that it is an improvement.

Another modification of the original Celanese fixture was designed in Royal Aircraft Establishment, U.K. Some details about the modified fixture can be found in Reference [32]. Soutis [33] and Curtis, et al. [32], have used this fixture to test thickness waisted specimens. Soutis [33] tested thickness waisted specimens with aluminum end tabs and obtained marginal improvements in compressive strengths compared to unwaisted specimens. Curtis, et al.[32], tested specimens with unidirectional plies in the core and equal number of $\pm 45^\circ$ plies on both sides of the core. The specimen was thickness waisted by machining off the $\pm 45^\circ$ plies in the gage section. This specimen configuration with integral end tabs produced considerably higher strength compared to the unwaisted specimens with aluminum end tabs.

There is at least one more modification of the basic Celanese test fixture that has received very limited circulation within the United States. One of these fixtures is known to exist at BASF [5], but its origin is uncertain. It may have been fabricated by Celanese personnel before the Celanese Fibers Division was purchased by BASF and the ownership of the fixture was transferred. Another of these fixtures exists at Lockheed Missiles and Space Co. [34], although again its origin is unknown. Perhaps it was also fabricated by Celanese for Lockheed some years ago. It appears that a standard Celanese fixture was reworked by machining a flat slot in each of the split cones, and fabricating flat wedge grips to fit in these slots, as shown in Figure 9 [34]. The result is a "grip within a grip", which can only be used successfully if the split cones are fully seated in their holders (for all of the reasons discussed relative to the standard Celanese fixture earlier). Thus, each pair of split cones and their holder are acting as one solid piece anyway, and might as well be fabricated as such, as done

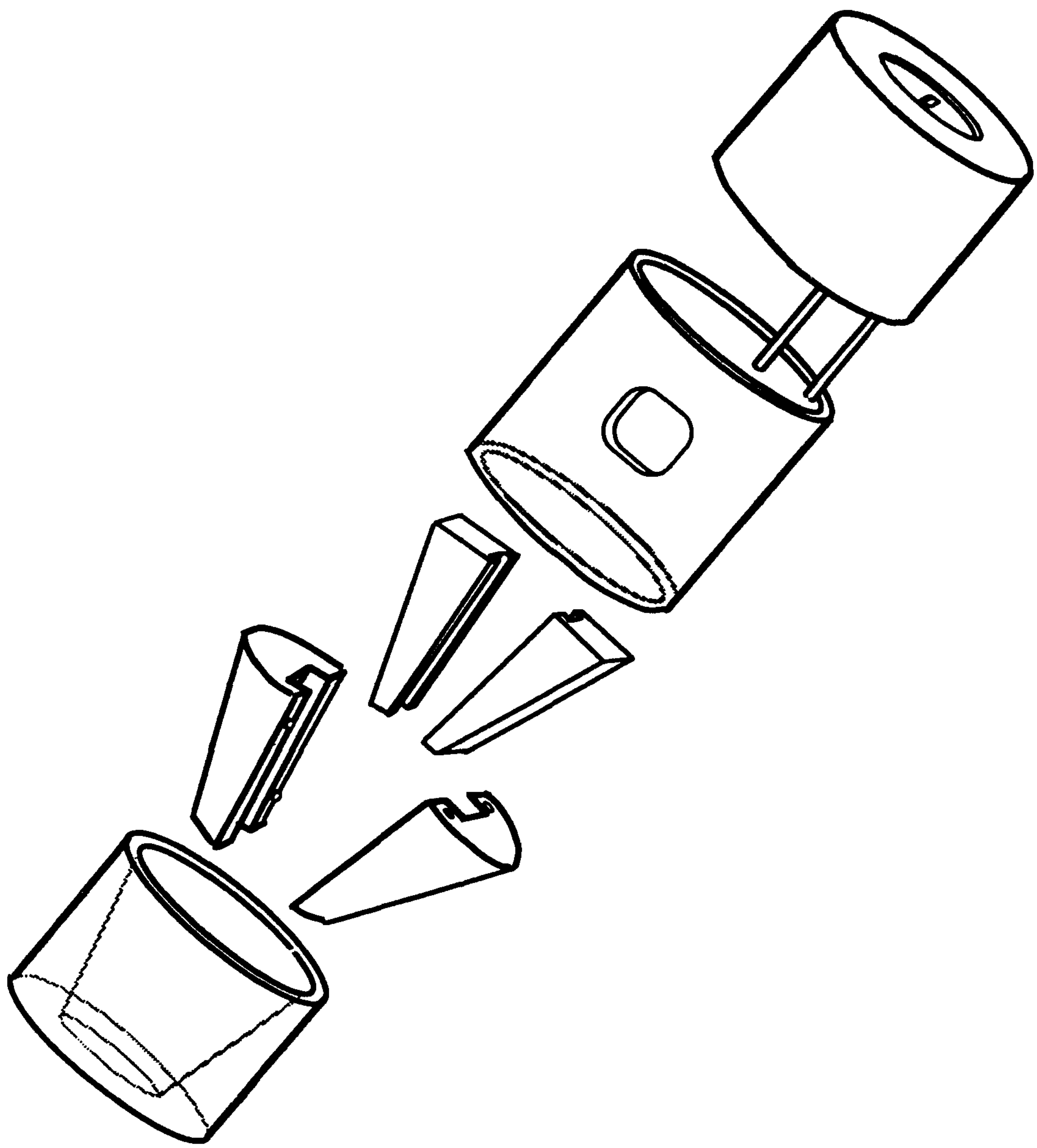


Figure 9. Lockheed/BASF Modification of Celanese Compression Test Fixture [5,34]

in the German modification [28,29]. It is for this reason that it is suspected that this fixture is a rework of an actual Celanese fixture, even though the history appears to be temporarily lost. Perhaps the motivation was the development of the German standard. On the other hand, it is curious that Adsit [4] makes the comment, referring to fixtures with flat wedge grips, that "... it was originally examined by Celanese investigators at the same time that the conical shaped wedge fixture was being developed."

Nevertheless, Pearson [34] used this fixture, comparing the results obtained for various composite materials with those he obtained using the ASTM D 695 test method, much the same as Vilsmeier, et al. [31] discussed above did, and with the same conclusions. That is, the modulus values compared well, but the compressive strengths obtained using the ASTM D 695 test method were lower, for the same probable reasons.

3.1.2 Wyoming-Modified Celanese Compression Test Method

General Description of the Test Method

A line drawing of the Wyoming-Modified Celanese compression test fixture is shown in Figure 10, and photographs of an actual fixture in Figure 11. This fixture was developed at the University of Wyoming in the late 1970's, and was immediately used successfully for both static and creep testing of high strength composite materials. A detailed description of the fixture was first published in the open literature in Reference [35]. Although minor improvements have been incorporated since that time, the basic concept has remained unchanged [9,25,26,36-38].

Relative to the standard Celanese fixture [1,2], it will be noted that the split-cone wedge grips have been replaced by tapered cylindrical wedge grips. Since these wedge grips have a constant radius along their entire length, and mate with holders of similar radius, the wedges always remain in full contact with the holders, independent of their relative axial position, i.e., independent of specimen thickness. Thus the friction resulting from the line contact between the conical grips and conical cavities in the original Celanese fixture has been avoided. In this sense they function much the same as the flat wedge surfaces of the IITRI fixture (Method B of Reference [1]). However, the stress concentrations induced at the square corners of the cavities in the IITRI end blocks are eliminated by the circular shape of the wedges. The loads

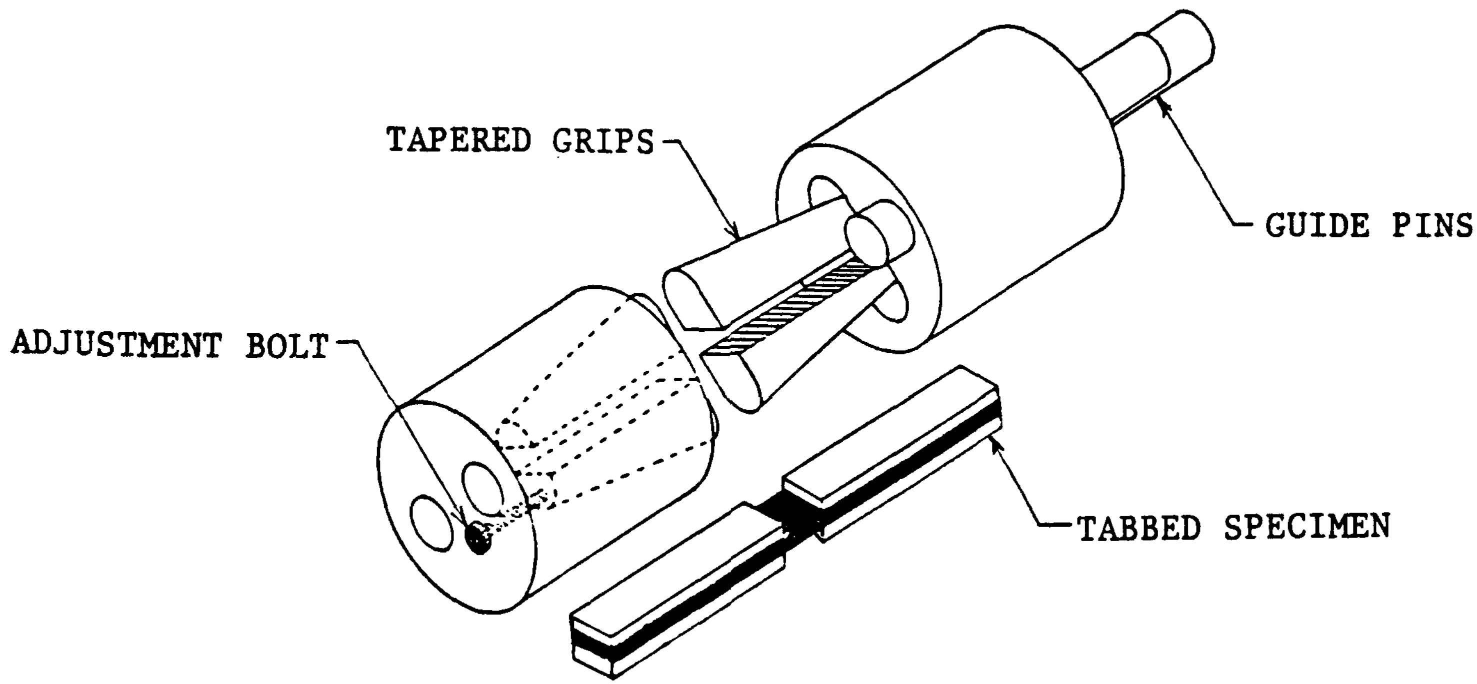
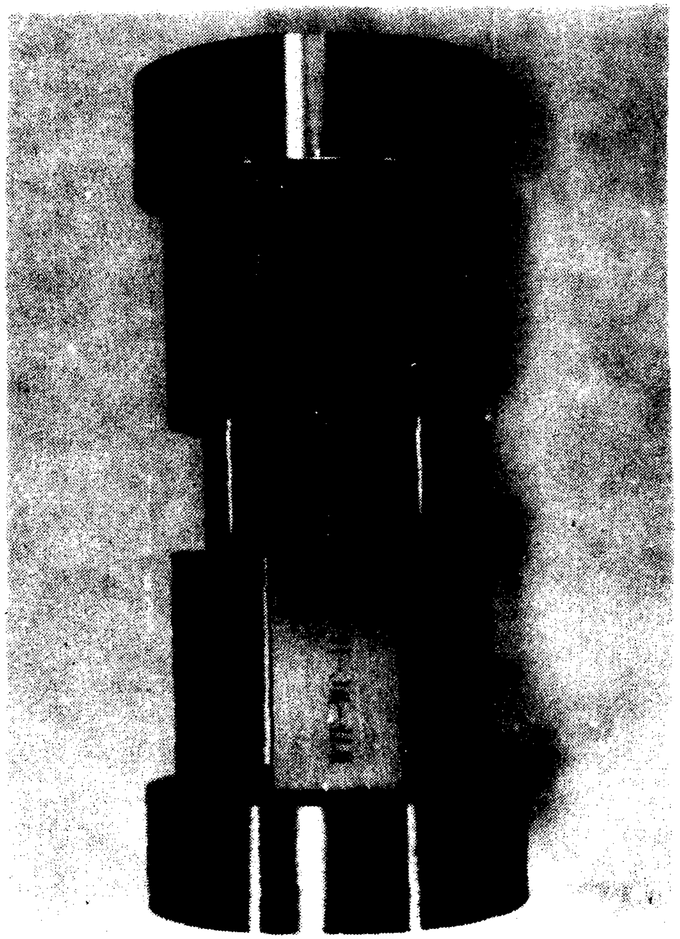
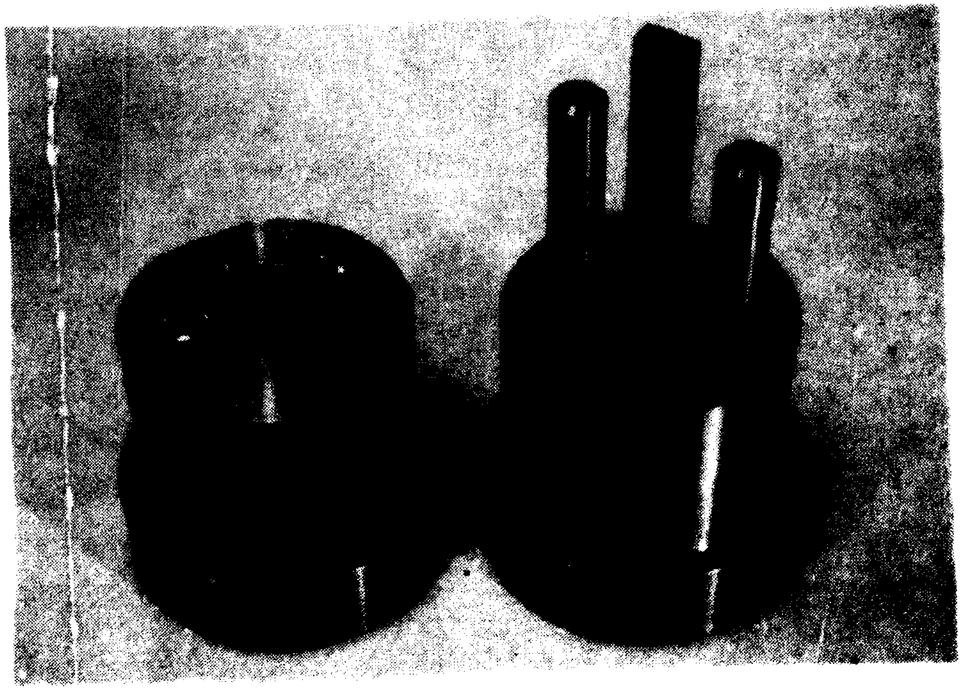


Figure 10. Schematic of Wyoming-Modified Celanese Compression Test Fixture [25]



Assembled Fixture With Specimen



Fixture Halves Separated

Figure 11. Wyoming-Modified Celanese Compression Test Fixture [9]

induced by the wedging action are more uniformly distributed into the end blocks. Also, by retaining the general circular geometry of the Celanese fixture, these loads are carried more efficiently, as hoop stresses. The end result is that the fixture can be much smaller and lighter than a corresponding miniature version of the standard IITRI fixture would be. For example, the Wyoming-Modified Celanese fixture weighs about 10 lb, almost exactly the same as the standard Celanese fixture [37,38]. In contrast, the IITRI fixture weighs over 90 lb [37,38]. This is not a fair comparison, however, as the IITRI fixture is capable of testing a specimen three times as wide, i.e., 1.50" wide versus 0.50" wide for the Wyoming-Modified Celanese fixture [9]. A better comparison is with the Wyoming-Modified IITRI fixture, which is essentially a miniature IITRI fixture, as will be discussed later, which also has a 0.50" specimen width capability, and weighs 23 lb [9,36-38]. This difference in fixture weight is significant when the fixture must be continually handled. It is also a factor for nonambient temperature testing, where the soak time required for the fixture to reach thermal equilibrium is a function of its mass.

The other significant change from the original Celanese fixture is the elimination of the troublesome alignment sleeve. Alignment is achieved using a pair of posts and linear ball bearings, just as with the IITRI fixture [1,21]. These precision-fit posts and recirculating ball bearings provide for minimal play, while making it essentially impossible to encounter binding. The use of posts and bearings rather than a sleeve also provides more ready access to the test specimen. For example, an extensometer can be readily used, if desired, rather than a strain gage.

Recessed socket-head cap screws are threaded into the outer ends of each of the four wedge grips so that the wedges can be pretightened onto the test specimen during its installation into the fixture. This permits each pair of wedges to be properly aligned with respect to each other, and also eliminates the need to seat the wedges on the specimen by preloading the fixture with a spacer bar installed between the pairs of wedge grips, as is done with the standard Celanese fixture.

The standard Wyoming-Modified Celanese test specimen is 4.5" long and 0.50" wide. This is 1" shorter than the 5.5" long standard specimen used with the standard Celanese and IITRI fixtures. Each tab is correspondingly 0.50" shorter, so that the gage length (distance between tabs) is still 0.50". The wedge grip taper angle has also been decreased from 10° to 8°. This provides a higher gripping force for a given axial compressive loading. It was felt

that such long tabs were unnecessary, and this has been proven over the more than ten years this fixture has been used in that no more tab problems have ever been encountered than with any of the other type of fixture. The shorter tabs permit shorter wedge grips, which reduces the size of the fixture.

The standard Wyoming-Modified Celanese test fixture [9] will accommodate a specimen of 0.15" to 0.25" thickness in the tab regions. For a specimen thickness of 0.25", approximately 0.25" of the wedge grips are protruding out from the holders, which is a readily acceptable amount. Thus, using two 1/16" thick tabs, the specimen itself can be 0.125" thick, which is usually ample. Of course, the fixture can be scaled up also, if desired [9]. Correspondingly, a longer or shorter specimen gage length than the standard 0.50" can be used.

Stress States and Failure Modes

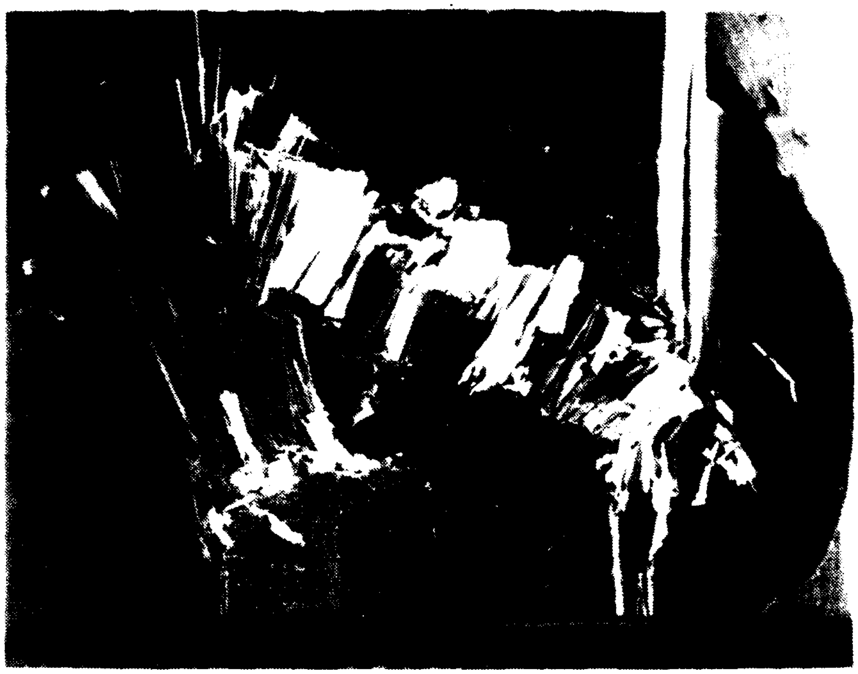
As for the Celanese, IITRI, and Wyoming-Modified IITRI compression tests, and all other methods relying on shear to transfer the load from the testing machine through fixture grips into the specimen, typically via tabs, there is a stress concentration induced in the test specimen due to the discontinuity in the region at the end of the gage length where the tab begins. This was discussed in detail with respect to the Celanese test method [1,2] in the previous section, and thus need not be repeated here. The tabs protect the composite material itself from damage by the grip faces. The standard Wyoming-Modified Celanese fixture does use relatively aggressive serrated grip faces, as do the IITRI and Wyoming-Modified IITRI fixtures [9]. However, ceramic particle-coated grip faces are now being used also, with good success [9].

Because of the stress concentrations present at the tab ends, failures commonly occur at, or even slightly inside the tabs [15], just as for the other compression test methods, including the Celanese compression test method discussed in the previous section. Correspondingly, the failure modes are very similar. Typical failures obtained using the Celanese compression test method were previously shown in Figure 3. Additional specimen failures are shown here for a unidirectional E-Glass/Epoxy unidirectional composite in Figures 12 through 14, for various environmental conditionings and test conditions, and for S-Glass/Epoxy and Carbon/Epoxy composites in Figure 15.

E-GLASS/EPOXY UNIDIRECTIONAL COMPOSITE, AXIAL COMPRESSION, NO PRECONDITIONING, ROOM TEMPERATURE TEST; INTERIOR SECTION EDGE VIEW.

THIS INTERIOR SECTION EDGE VIEW OF A FAILED COMPRESSION SPECIMEN SHOWS THE TYPICAL FAILURE MODE, NAMELY BUCKLING AT A 45^0 ANGLE TO THE LOAD DIRECTION. UNIQUE CHARACTERISTICS EXHIBITED IN THIS PHOTOGRAPH ARE THE LARGE CRACKS PARALLEL TO THE FIBERS (LONGITUDINAL SPLITTING) AND THE MANY LOOSE BUCKLED FIBERS.

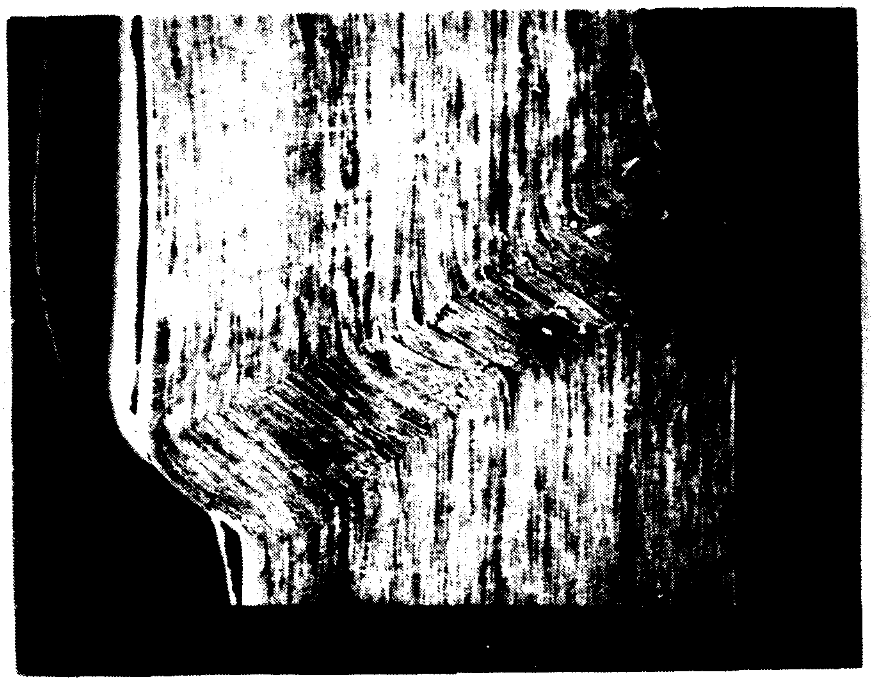
Figure 12. E-Glass/Epoxy Unidirectional Composite, Axial Compression, No Preconditioning, Room Temperature Test; Interior Section Edge View (Scanning Electron Microscope, 18X Magnification) [6]



E-GLASS/EPOXY UNIDIRECTIONAL COMPOSITE, AXIAL COMPRESSION, 98% RH, 75^{0}C PRECONDITIONING, ROOM TEMPERATURE TEST.

THIS EDGE VIEW OF A FAILED COMPRESSION SPECIMEN IS SIMILAR TO THAT OF A NONCONDITIONED SPECIMEN ALSO TESTED AT ROOM TEMPERATURE. THE DIFFERENCES INCLUDE LESS DOMINANT LONGITUDINAL CRACKING, AND MORE BUCKLED FIBER BUNDLES. THE SMALL LONGITUDINAL SPLIT ON THE CENTER LEFT SIDE WAS HALTED BY ANOTHER SMALL BUCKLING FAILURE SEEN AT THE LEFT FACE. COMPARISON WITH AN ELEVATED TEMPERATURE SPECIMEN INDICATES CONSIDERABLY MORE FRAGMENTATION OR BRITTLE FAILURE AT THIS LOWER TEST TEMPERATURE.

Figure 13. E-Glass/Epoxy Unidirectional Composite, Axial Compression, 98% RH, 75 °C Preconditioning, Room Temperature Test; Interior Section Edge View of Specimen (Scanning Electron Microscope, 20X Magnification) [6]



E-GLASS/EPOXY UNIDIRECTIONAL COMPOSITE, AXIAL COMPRESSION, 98% RH, 75°C PRECONDITIONING, 121°C TEST TEMPERATURE.

THIS PHOTOGRAPH IS AN EXCELLENT EXAMPLE OF A CLASSICAL BUCKLING FAILURE. AT THIS ELEVATED TEMPERATURE THERE IS ENOUGH COMPLIANCE OF THE MATRIX TO KEEP THE SPECIMEN INTACT EVEN THOUGH MOST OF THE FIBERS HAVE BEEN BROKEN.

Figure 14. E-Glass/Epoxy Unidirectional Composite, Axial Compression, 98% RH, 75°C Preconditioning, 121°C Test Temperature; Interior Section Edge View of Specimen (Scanning Electron Microscope, 24X Magnification) [6]

Figure 15. Typical Failures of Wyoming-Modified Celanese Compression Test Specimens [25]

a) AS4/3501-6 $[0]_{16}$ Carbon/Epoxy
b) S2/3501-6 $[0]_{32}$ Glass/Epoxy
c) AS4/3501-6 $[45/0/-45/90]_{3s}$ Carbon/Epoxy
d) S2/3501-6 $[45/0/-45/90]_{4s}$ Glass/Epoxy

As for all of the other shear-loaded and end-loaded compression test methods, the compressive stress is simply the applied force at failure divided by the cross-sectional area of the gage section of the specimen, i.e., $\sigma = P/A$.

When using the Wyoming-Modified Celanese compression test fixture, there is ample room to use an extensometer to measure strains, if desired. The extensometer can be mounted on the specimen before it is installed in the test fixture, or after.

As with any compression test, whenever there is any concern about specimen bending or buckling, it is necessary to use instrumentation on both of the surfaces of the specimen that are outboard from the minimum moment of inertia axis. For a specimen of rectangular cross section such as the Wyoming-Modified Celanese, these are the 0.50" wide surfaces. While in theory two axial extensometers could be used, it is more common to use two axial strain gages instead. The two gage readings will readily indicate whether bending or buckling is present, as previously discussed in detail with respect to the Celanese test method.

Other Requirements and Modifications

Because of the use of tapered cylindrical wedge grips, the thickness of the specimen in the tabbed regions is not fixed. Thus, if the tabs can be bonded onto the composite with relatively equal adhesive bond line thicknesses on each side, and the outer surfaces of opposing tabs are parallel to each other, no final tab machining or other additional preparation is required prior to testing. As previously discussed, it is convenient to use some type of alignment jig during tab bonding.

As in most cases, it has been found that the precision of the fixture is also very critical to the success of the Wyoming-Modified Celanese compression test method [25,26]. The tapered cylindrical surfaces of the hardened tool steel wedge grips must fit properly in their holders, and a high quality finish on these mating surfaces is important also. This cannot occur unless the individual components are very accurately machined.

Good alignment between the grips is well-maintained in the Wyoming-Modified Celanese fixture, by the two 0.50" diameter hardened steel posts with linear ball bearings. This, in combination with the recommended use of a spherical seat, makes the test fixture relatively forgiving of load train misalignments. As a result, scatter of the data reported in the literature

for the Wyoming-Modified Celanese compression test method is at least as low as that obtained using any of the other compression test methods [25,26,36].

In summary, it is possible to measure compressive strength and modulus just as accurately with the Wyoming-Modified Celanese compression test method as with any competing method. Equally important, it appears that the test fixture is as forgiving as any of the others to specimen irregularities, is compact and lightweight, and relatively easy to use.

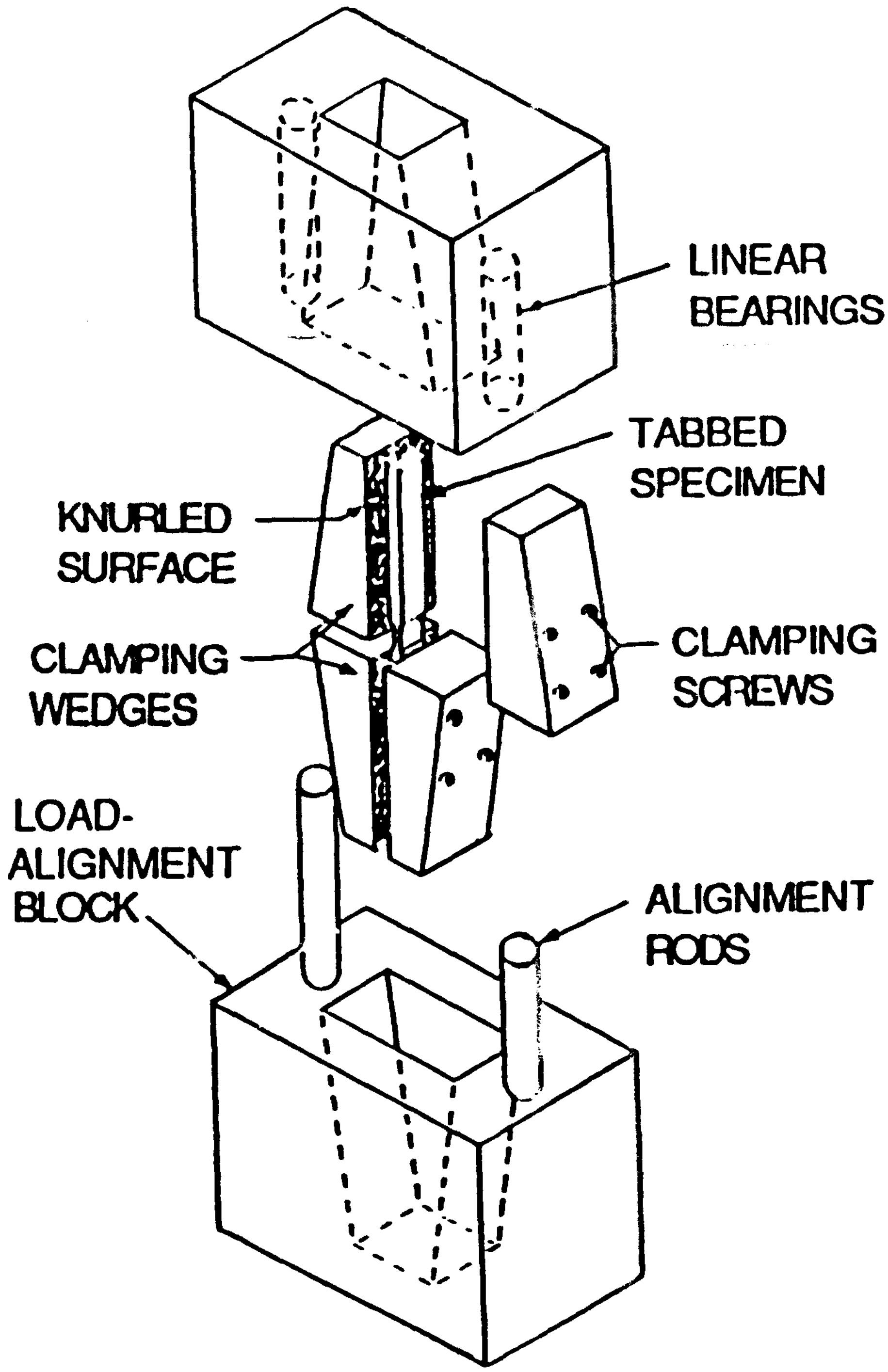
3.1.3 IITRI Compression Test Method

General Description of the Test Method

The IITRI compression test method was developed b Hofer and Rao [21] at the Illinois Institute of Technology Research Institute (IITRI) in the mid-1970's, as a fixture to eliminate the various deficiencies already discussed here for the Celanese compression test fixture, which had been introduced in 1971 [2,3] and was standardized by ASTM in 1975, as ASTM Standard D 3410 [1]. The IITRI fixture did not become an ASTM standard until 1987 when, after a round-robin evaluation [4], it was added to the existing Celanese standard, viz., as Method B of ASTM Standard D 3410 [1]. (The Sandwich Beam Flexure Compression Test Method was also subjected to the same round-robin evaluation at that time, and also added to the Standard, as Method C. The Modified ASTM D 695 fixture was also evaluated, but was not considered acceptable [4].)

It is interesting that Hofer and Rao [21] chose to design such a massive IITRI test fixture to replace the much smaller Celanese fixture. It will be recalled that the Celanese fixture can accommodate a specimen up to only 0.25" wide, and of very limited thickness. While Reference [21] does not indicate the maximum width of specimen the original IITRI fixture could accommodate, the specimens they used appear from the photographs to be about the same width as Celanese specimens, i.e., only about 0.25".

The IITRI fixture has not changed significantly since it was introduced in 1977 [21]. In fact, many of the configurations now commercially available look identical to the original. A schematic of such a fixture is shown in Figure 16. The width of specimen a particular fixture can accommodate is dependent on the design of the wedge grips. In some current designs, the capacity of the wedge grips is as little as 0.25" or 0.50", even though the overall fixture



IITRI COMPRESSION TEST FIXTURE

Figure 16. Schematic of Basic IITRI Compression Test Fixture Design [22]

itself is full size. The governing ASTM Standard D 3410 [1] actually defines four fixture sizes, to accommodate specimens up to 0.25", 0.50", 1.00", and 1.50" wide, respectively. Also, each fixture size can include several sets of wedge inserts in the end blocks, to accommodate specimens of different ranges of thicknesses. In the ASTM Standard, three size ranges are specifically defined, and are the same for all four fixture sizes, i.e., specimen thickness ranges (in the tabbed region) from 0.030" to 0.100", from 0.100" to 0.250", and from 0.250" to 0.400".

Clark and Lisagor [39] found that the IITRI fixture was sensitive to the flatness and parallelism of the specimens. If the tab surfaces on the specimens were not perfectly flat and parallel, nonuniformity in strain were induced across the specimens. This strain nonuniformity resulted in lower compressive strength of the specimens. When the specimen tabs were ground to be flat and parallel, uniformity in strain across the specimen was achieved. However, one must be careful not to introduce any asymmetry in the specimen while making it flat and parallel. The authors also found that $[\pm 45/\mp 45]_{2S}$ laminates tested in the IITRI fixture showed a dependency of the compressive strength on specimen width. The authors attributed the dependency to the probable biaxial stress state present in the specimens. Port [40], using the RAE compression test method, also found that there was a width effect on compressive strength of laminates consisting of unidirectional and $\pm 45°$ plies. He attributed it to the possibility of nonuniform load input. Therefore, one must take necessary precautions while testing wide specimens.

The upper block of the IITRI fixture is typically bolted to the crosshead of the testing machine [1,21]. The wedge grips have broad, flat surfaces, which make full contact with the mating flat surfaces in the end block cavities. This results in a very stable configuration. Large diameter (0.750") posts and linear bearings are also used, further adding to the rigidity of the system, while maintaining alignment between the fixture halves. The wedge grip pairs can be clamped together with screws, to hold the test specimen in place during installation. This also permits seating the wedge grips, so that the specimen does not slip in them when the compressive loading is first applied. One advantage of the IITRI fixture is that the grips can be taken out of the fixture to install the specimen in the grips. This feature helps in easier installation and alignment of the specimens in the grips.

Although the test fixture is massive as originally designed by IITRI, i.e., the original fixture probably weighed on the order of 75 lb, once it is installed in the testing machine only

the wedge grips themselves must be repeatedly handled by the operator while performing the testing. However, the large size of the fixture does make its cost high, being on the order of three times that of the Wyoming-Modified Celanese test fixture [9], for example.

The standard IITRI specimen is 5.5" long, the same as the Celanese specimen. Tabbing conditions as specified in the ASTM Standard [1] are also the same, as discussed previously for the Celanese Test Method.

One unique feature of the IITRI fixture as sketched in ASTM Standard D 3410 [1] is the provision for using end loading bars in the wedge grips. Although not discussed anywhere in the Standard, and therefore very easy to overlook, it will be noted in Figure 3b of ASTM Standard D 3410 [1], repeated here as Figure 17, that a transverse keyway across the gripping surface is shown at the narrow end of the wedge grip. A bar (key) can be placed between mating wedge grips in these key ways. The ends of the test specimen are then butted up against these end loading bars before the wedges are clamped together. As the specimen is loaded, a portion of the applied loading is transmitted through the specimen ends and the remainder via shear through the grip faces. Of course, the specimen must be made slightly shorter in the tab regions if the 0.50" distance between wedge grips is to be maintained. That is, some of the tab will extend out from the wedge grip if the tab is not shortened. Not all commercially available IITRI fixtures include these keyways in the wedge grips, or the end loading bars, and in fact they do not seem to be used very often. One reason perhaps is that when testing most composite materials they are not needed. The serrated (or flame sprayed) faces of the wedge grips are themselves sufficient to hold the specimen. However, as newer, stronger, thicker and more difficult to test composites are continually developed, it is important to remember that this ability to obtain a combined end- and shear-loading does exist with the IITRI fixture [9]. The concept appears sound. Incidently, there is no mention of end-loading bars in the original Hofer and Rao paper [21], suggesting that this feature may have been added by someone at a later time. The grips of an actual IITRI fixture [9] that does contain the transverse keyways and loading bars are shown in Figure 18.

Finally, it should be noted that the same Figure 3b of the ASTM Standard D 3410 [1], repeated as Figure 17 and referred to above, also suggests the use of flame-sprayed powdered molybdenum as a grip face friction material.

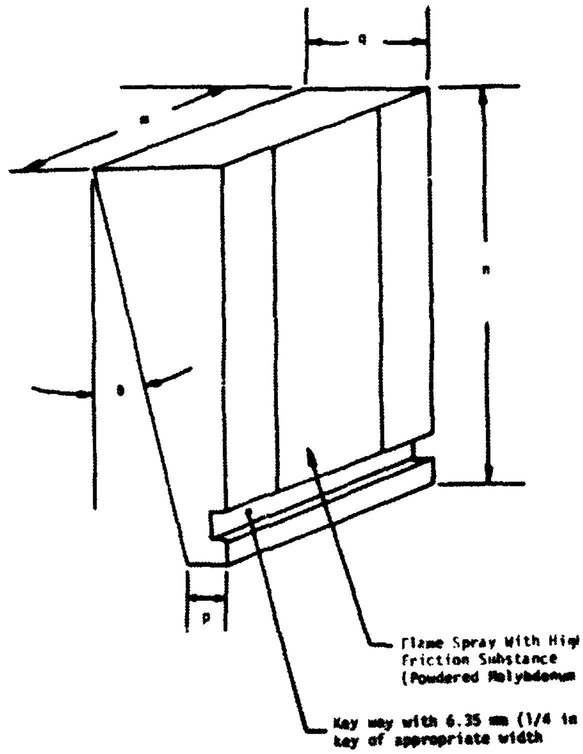


Figure 17. Detail of Wedge Design for Procedure B (IITRI) Test Fixture (Figure 3b of ASTM Standard D 3410-87 [1])

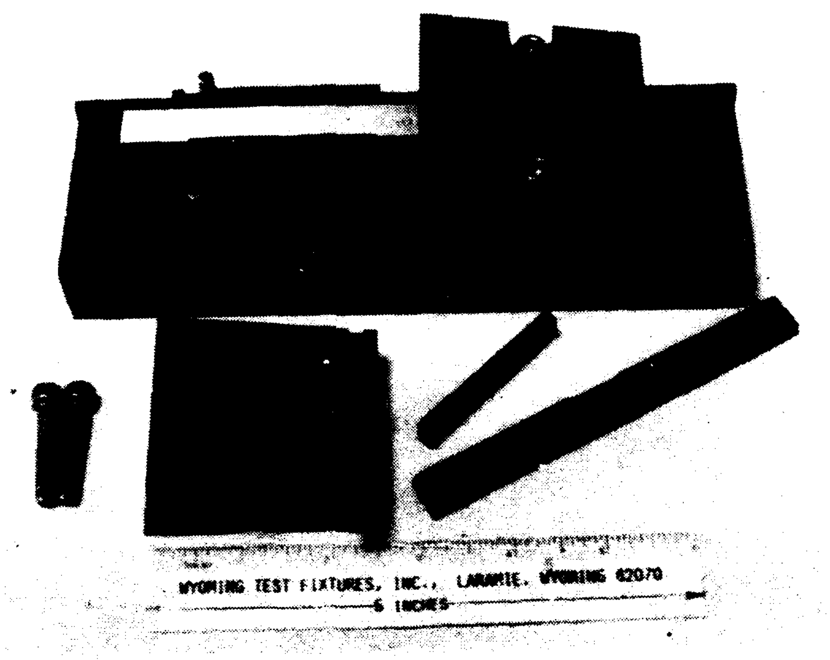
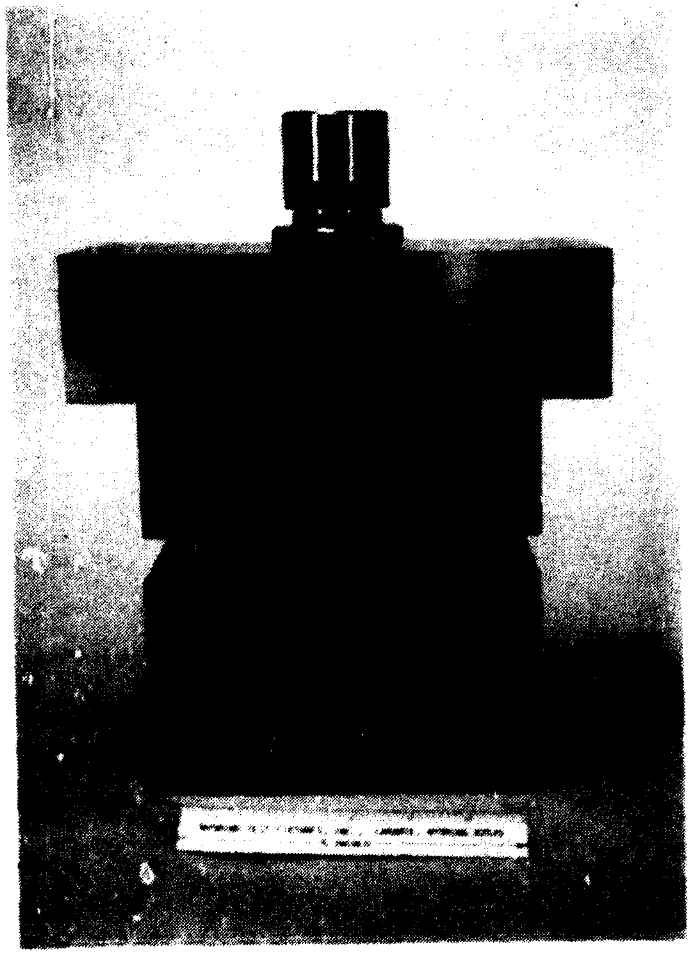


Figure 18. Specimen Installation Jig for Use with IITRI Compression Test Fixture, Showing Test Specimens, Alignment Bar, and End Loading Bar [9]

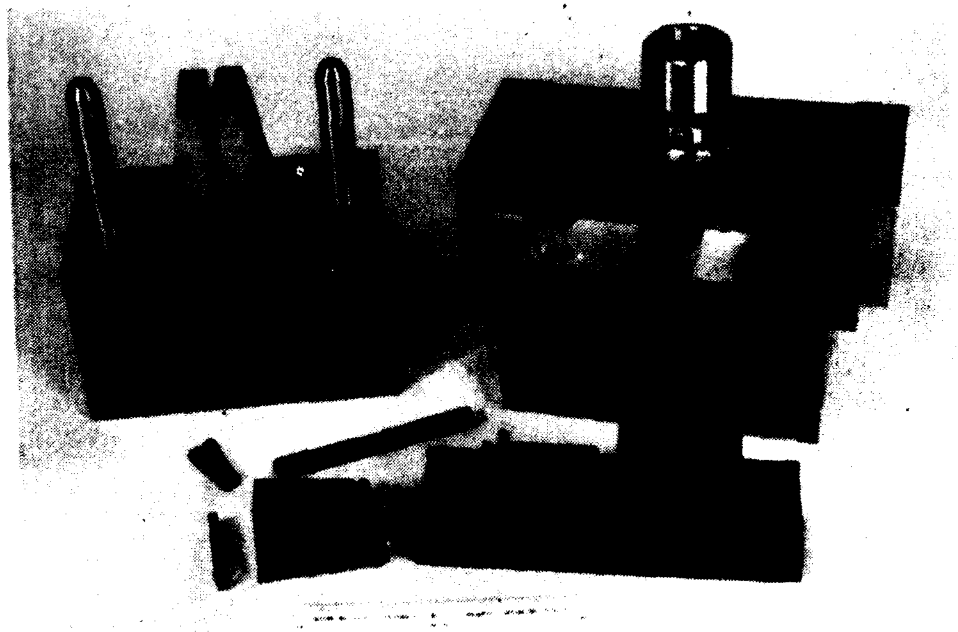
Photographs of an actual IITRI test fixture are shown in Figure 19. The cutouts in the grip faces for the end-loading bars can be seen. Three pairs of end-loading bars are provided, of different widths, to cover the three ranges of specimen thicknesses covered by the interchangeable wedge spacers provided with the fixture. In fact, this particular fixture [9] covers a broader range of specimen thicknesses than indicated in the ASTM Standard: Low Range: 0.14" to 0.35"; Medium Range: 0.29" to 0.47", and High Range: 0.42" to 0.60". It will be noted that the thickest specimen accommodated is 50 percent greater than specified in the ASTM Standard. This maximum thickness of 0.60" permits the testing of a relatively thick tabbed composite specimen.

It will also be noted that the wedge grips are resting in a special specimen installation jig, that holds the lower halves horizontal and at the proper 0.50" gage length spacing while the specimen is being installed. This very convenient accessory [9] was previously shown in Figure 18 also. As can be seen, a spacer bar indexed against the alignment pins is used to center the specimen in the grips [9]. Since this particular fixture can accommodate a specimen of any width up to a full 1.50", spacer bars of various widths are provided, to accommodate specimens 0.25" 0.50", 0.75", 1.00" and 1.50" wide [9]. Of course, spacer bars of any other width can be provided also, if required.

Another important feature of this particular IITRI fixture is the use of the C-shaped holder at the top, that attaches directly to the load cell/crosshead of the testing machine with its own adaptor [9]. This holder and adaptor weighs only about 15 lb, and thus is much easier to hold while attaching to the load cell. The upper end block then simply slips into this holder. In the standard IITRI fixture version (see Figure 16), the entire 30 to 35 lb upper end block has to be held while being bolted in place to the crosshead of the testing machine. While the holder is a very significant convenience item, even more important is its presence if the upper wedge grips become stuck in the upper end block when a specimen explosively fails. This does occasionally happen. The upper end block can then simply be slid out of the holder, as indicated in Figure 18, which exposes the back side of the wedge grips which can then be tapped loose. No problem is presented if the wedges stick in the lower holder as it is not normally attached to the base of the testing machine. It can be simply tipped on its side and the wedge grips tapped loose.



Assembled Fixture



Partially Assembled Fixture With Specimen Installation Jig
and Extra Pair of Specimen Grips

Figure 19. IITRI Compression Test Fixture [9]

Stress States and Failure Modes

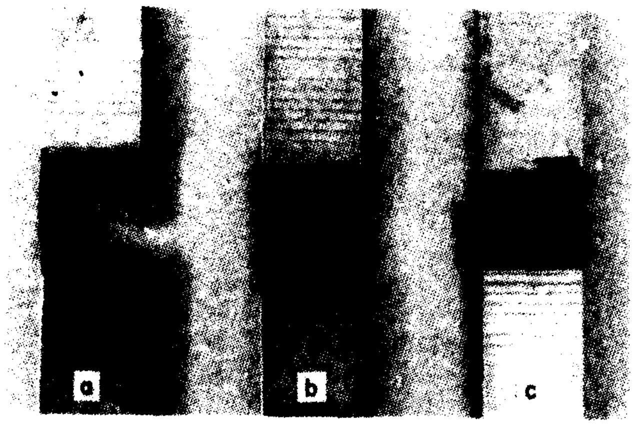
As for the Celanese, Wyoming-Modified Celanese, and Wyoming-Modified IITRI compression tests, and all other methods relying on shear to transfer the load from the testing machine through fixture grips into the specimen, typically via tabs, there is a stress concentration induced in the test specimen due to the discontinuity in the region at the end of the gage length where the tab begins. This was discussed in detail with respect to the Celanese test method above, and thus need not be repeated here.

Because of the stress concentrations present at the tab ends, failures commonly occur at, or even slightly inside the tabs [15], just as for the other test methods. Correspondingly, the failure modes are very similar. Typical failures obtained using the IITRI test fixture are shown in the multiple photographs of Figure 20 [15]. The failure modes identified in these photographs are defined in the sketches of Figures 21 and 22. The occurrence of these various failure modes as a function of measured compressive strength and type of tabs used (see Figure 4 for definitions of tabbing conditions) is indicated in Figure 23. The result of this study was that, even though various failure modes could be identified, their occurrence did not correlate with the level of compressive strength achieved [15].

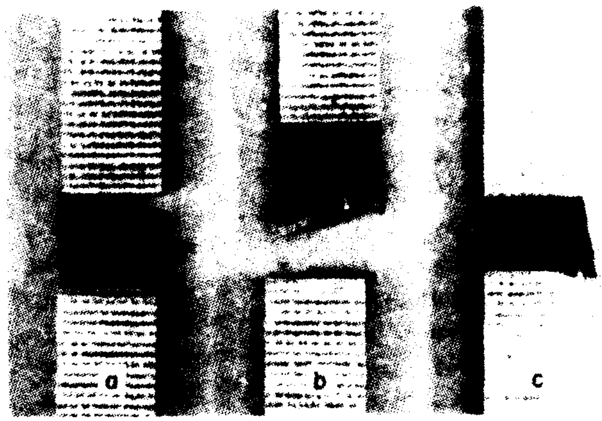
As for all of the other shear-loaded and end-loaded compression test methods, the compressive stress is simply the applied force at failure divided by the cross-sectional area of the gage section of the specimen, i.e., $\sigma = P/A$.

Because of the physical size of the IITRI test fixture and the fact that there is only between 1/2" and 1" of space between the upper and lower grip holders (depending upon how much each wedge grip is protruding from the holders), it is difficult to use an extensometer on the test specimen. It can be done but the reach distance is so great that the overhang is excessive [25,26]. Thus it is more practical to use a strain gage to measure strains.

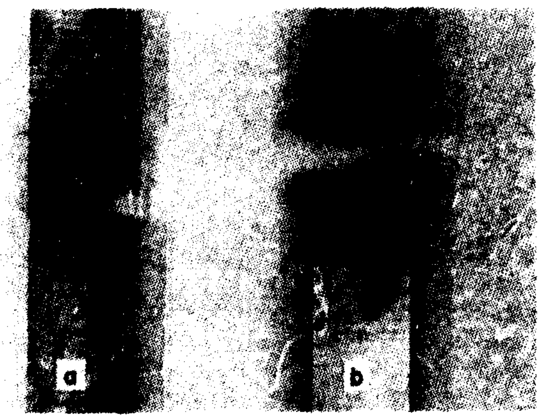
As with any compression test, whenever there is any concern about specimen bending or buckling, it is necessary to use instrumentation on both of the surfaces of the specimen that are outboard from the minimum moment of inertia axis. For a specimen of rectangular cross section such as IITRI, these are the wide surfaces. The two gage readings will readily indicate whether bending or buckling is present, as previously discussed in detail with respect to the Celanese compression test method.



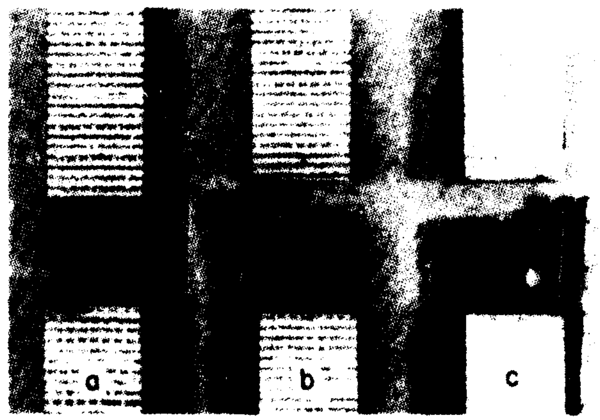
Failure modes of tapered steel tabbed specimens: (a) branched transverse; (b) transverse; and (c) broomed



Failure modes of untapered glass/epoxy tabbed specimens: (a) branched transverse; (b) transverse; and (c) broomed

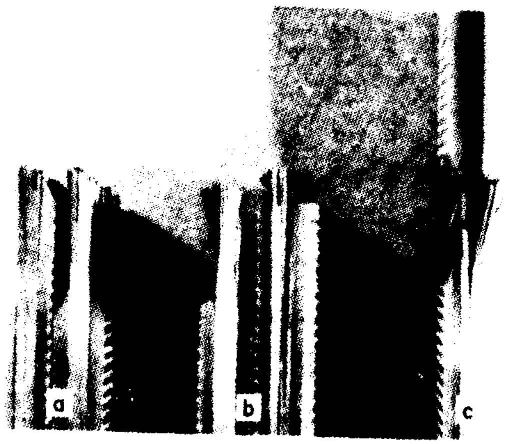


Failure modes of untapered steel tabbed specimens with different gripping conditions: (a) branched transverse failure mode for a partially gripped specimen; and (b) split transverse failure mode for a fully gripped specimen

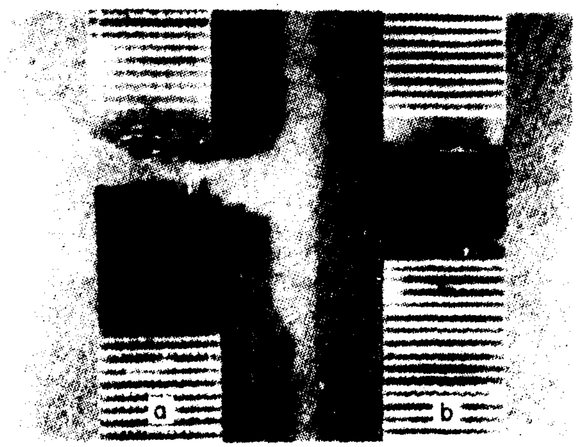


Failure modes of untapered glass/epoxy tabbed specimens as influenced by tab debonding: (a) transverse failure mode of a specimen with tabs fully bonded; (b) split transverse failure mode of a specimen with 6.4 mm of the tab length debonded; and (c) split transverse failure mode of a specimen with 12.7 mm of the tab length debonded

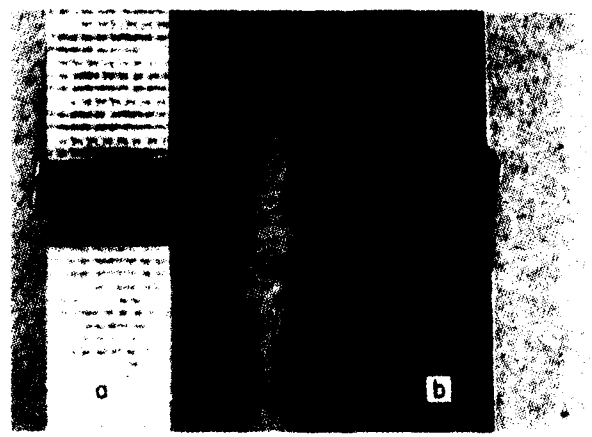
Figure 20. Examples of Compressive Failure Modes of Unidirectional AS4/3501-6 Carbon/Epoxy Composites Tested Using an IITRI Test Fixture and Various Tabbing Conditions [15]



Side views of failure modes for glass/epoxy tabbed specimens: (a) tapered tab specimen, *indicating that the failure* plane is not parallel to the specimen thickness; (b) untapered tabbed specimen, indicating that the failure plane is parallel to the specimen thickness; and (c) broomed failure mode

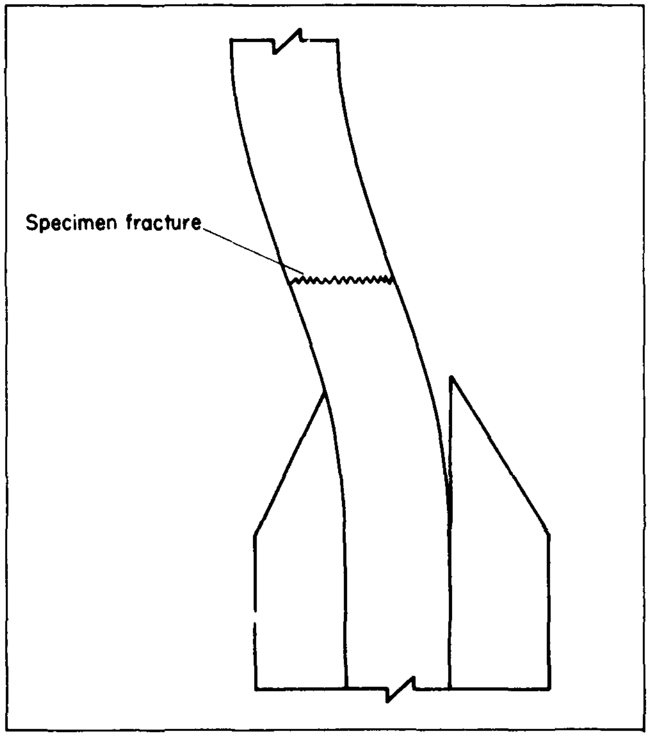


Failure modes of tapered glass/epoxy tabbed specimens: (a) shear failure mode that resulted from specimen buckling; and (b) broomed failure mode

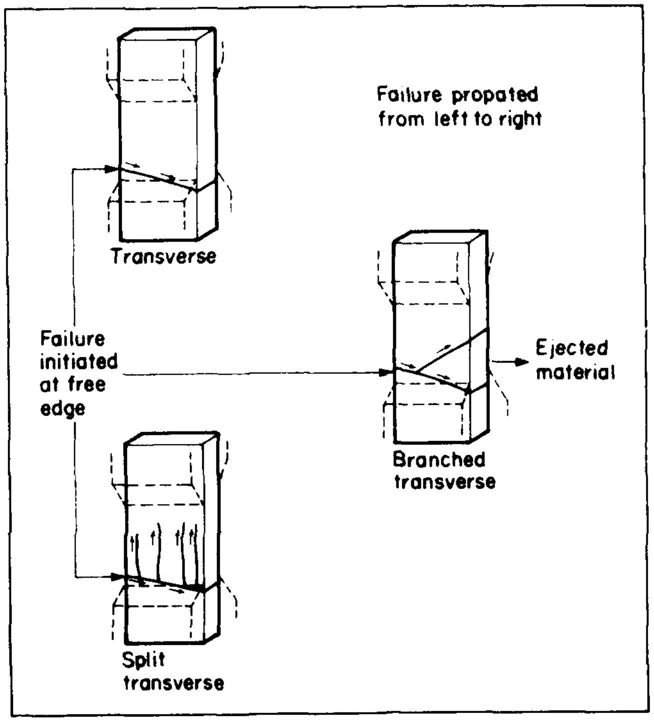


Broomed failure modes: (a) untapered glass/epoxy tabbed specimen; and (b) tapered steel tabbed specimen

Figure 20. Examples of Compressive Failure Modes of Unidirectional AS4/3501-6 Carbon/Epoxy Composites Tested Using an IITRI Test Fixture and Various Tabbing Conditions [15] (Cont'd.)



Specimen deformation due to buckling, and corresponding location of final fracture

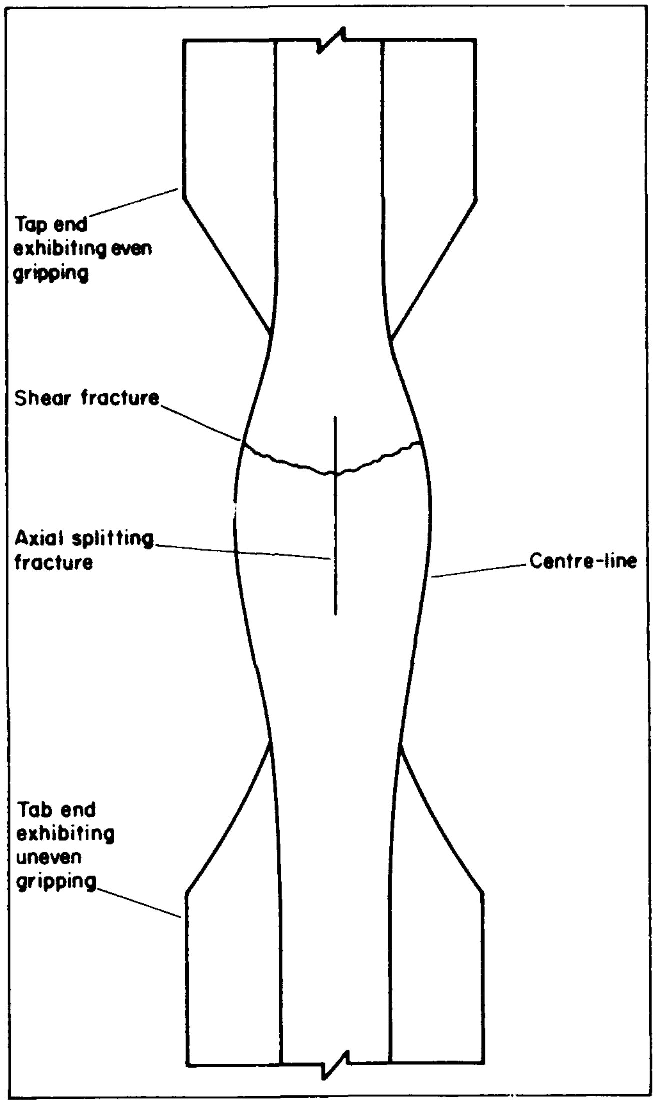


Failure progression for compression specimens exhibiting transverse failure modes

Specimen Deformation Due to Buckling, and Corresponding Location of Final Fracture

Failure Progression for Compression Specimens Exhibiting Transverse Failure Modes

Figure 21. Sketches of Typical Compressive Failure Modes Observed for Unidirectional AS4/3501-6 Carbon/Epoxy Tested Using Composites Tested Using an IITRI Test Fixture [15]



Deformed shape prior to failure of a specimen that exhibited a brooming failure mode

Figure 22. Deformed Shape Prior to Failure of a Specimen that Exhibited a Brooming Failure Mode [15]

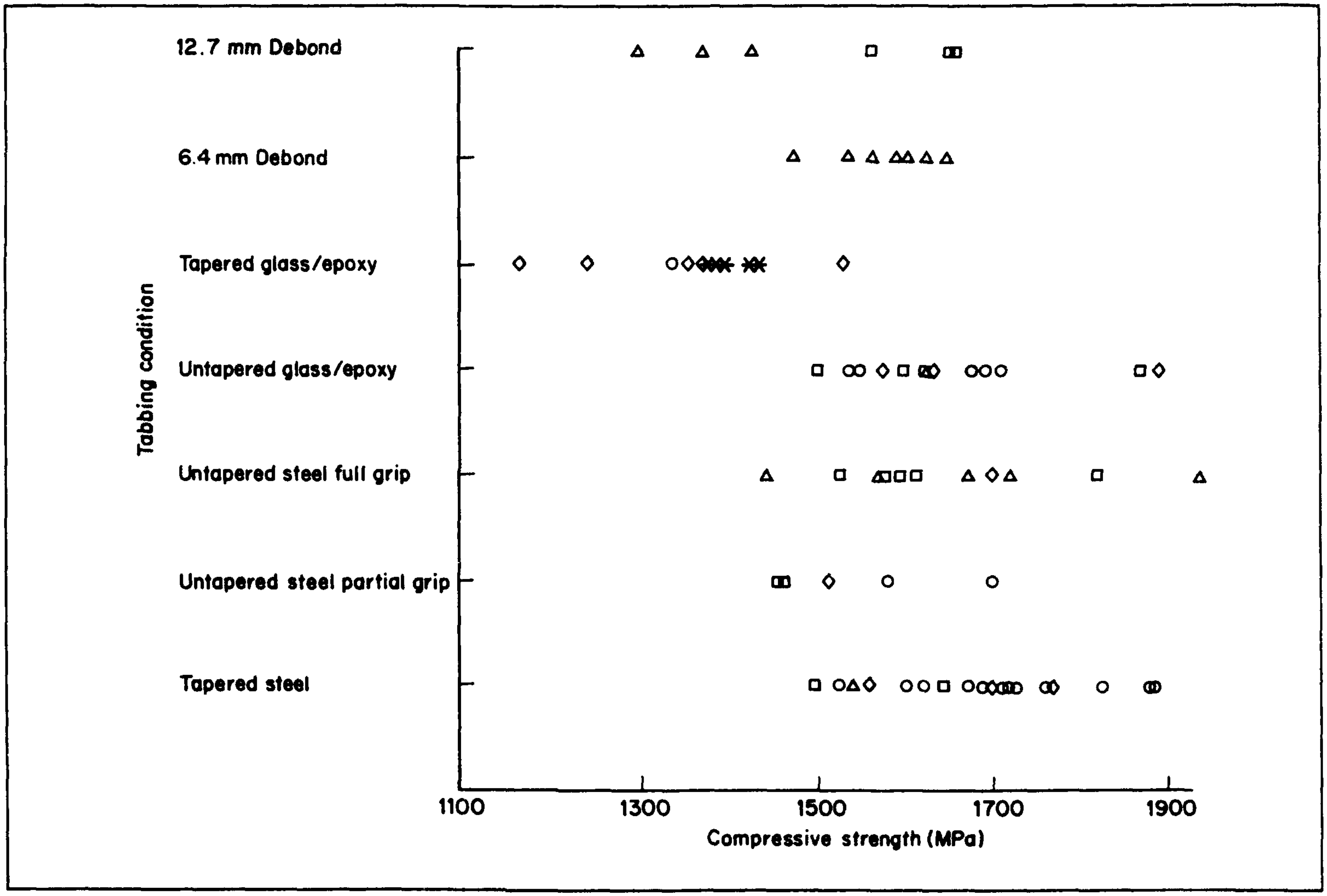


Figure 23. Failure Modes as Related to Measured Compressive Strength and Tabbing Condition [15].
Observed Failure Modes:
○, branched transverse; □, transverse; △, split transverse; ◇, broomed; *, shear

Ryder and Black [41], while using an end-loaded, side-supported fixture to test large gage length composite coupons, observed that extensometer type or attachment seemed to have some marginal effect on the measured composite compressive strength. Berg and Adams [25,26], however, showed that strain gages and extensometers gave comparable results. While using extensometers, one must be careful so that the knife-edges of the extensometer do not slip or do any surface damage to the specimens.

Other Requirements and Modifications

Because of the use of flat tapered wedge grips, the thickness of the specimen in the tabbed regions is not fixed. In fact, as previously presented, the IITRI fixture, because of its large size, can accommodate a very wide range of specimen thicknesses. Thus, if the tabs of equal thickness can be bonded onto the composite with relatively equal adhesive bond line thicknesses on each side, and the outer surfaces of opposing tabs are parallel to each other, no final tab machining or other additional preparation is required prior to testing. As previously discussed, it is convenient, however, to use some type of alignment jig during tab bonding. Using the very aggressive serrated wedge grip faces rather than the much smoother flame sprayed faces is also an advantage in this regard as the aggressive grips will dig deeply into the tab surface, negating any local surface irregularities such as slight high spots.

As in most cases, it has been found that the precision of the fixture is also very critical to the success of the IITRI compression test method [25,26]. The tapered flat surfaces of the hardened tool steel wedge grips must mate properly with their holders, and a high quality finish on these mating surfaces is important also. This cannot occur unless the individual components are very accurately machined. For example, a high spot on one of the mating surfaces between the wedge grip and the spacer wedge it is sliding on can result in that wedge abruptly hanging up as the compressive loading is being applied. This will induce a strong bending moment in the specimen, as shown by the actual experimental data presented in Figure 24 [25,26]. It will be noted that one strain gage reading suddenly begins to increase rapidly, while the other decreases, just as was discussed in detail previously with respect to buckling of a Celanese test specimen. However, in the present case, it is due to abrupt bending. In the case shown here in Figure 24, the wedge just as abruptly broke loose, and both gage readings returned to their normal paths. Note that if the test had been terminated

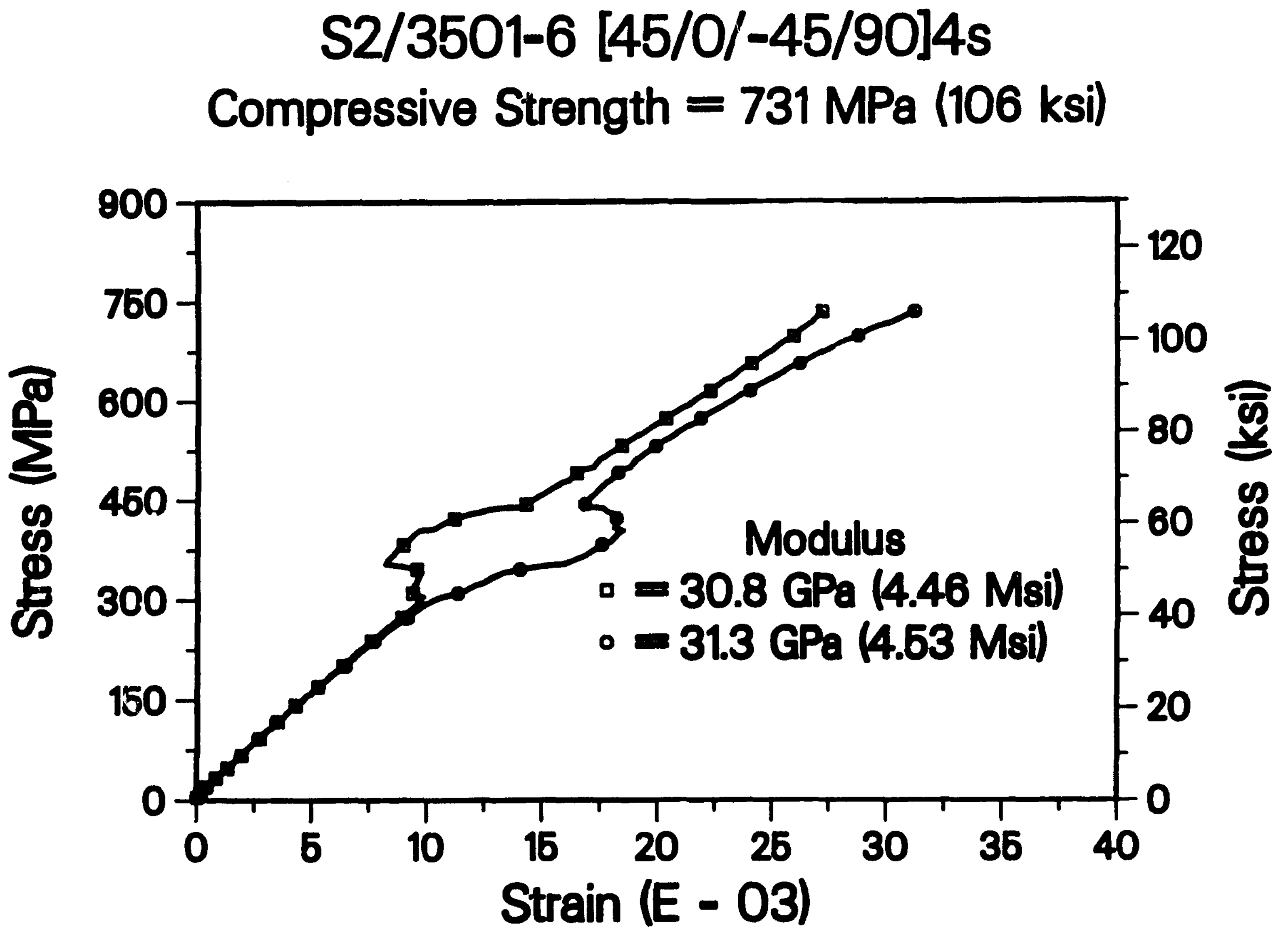


Figure 24. Axial Compression of a Quasi-Isotropic S2/3501-6 Glass/Epoxy Composite Material Tested in an IITRI Compression Test Fixture Exhibiting a Wedge Grip Seating Anomoly [25]

at a point before the wedge broke loose, or if it had not, the corresponding stress-strain plot would appear as if a buckling failure had occurred. In the present case it was discovered that the wedge grip surface did have a slightly high spot. Once it was removed, no further problems were encountered in future testing. Similar problems can be encountered with other types of fixture imperfections, e.g., binding of the alignment pins between wedge grip halves as the tab is compressed under loading, and excessive machining tolerances in general [25,26].

Good alignment between the grips is maintained in the IITRI fixture, by the two 0.75" diameter hardened steel posts with linear ball bearings. This, in combination with the high rigidity of the massive fixture, and the recommended use of a spherical seat [1], makes the test fixture relatively forgiving of load train misalignments. As a result, scatter of the data reported in the literature for the IITRI compression test method is at least as low as that obtained using any of the other compression test methods, and often better [7,10, 25,26,36].

In summary, it is possible to measure compressive strength and modulus at least as accurately with the IITRI compression test method as with any competing method. If the high cost of the test fixture and the inconvenience of having to manipulate its great mass can be overcome, the IITRI test method may be the most reliable compression test method currently available for testing high strength composite materials.

3.1.4 Wyoming-Modified IITRI Compression Test Method

General Description of the Test Method

The Wyoming-Modified IITRI compression test method was developed at the University of Wyoming [6,9,36] as a less massive, lower fabrication cost alternative to the standard IITRI test fixture described in the previous section. It is essentially a miniature IITRI. Because it is smaller, it does not have the specimen width or thickness capacity of the standard IITRI fixture. While a modified fixture of any size could be designed and fabricated, and in fact other sizes have been made [9], the fixture standardized by the University of Wyoming [6,36] has the capability of testing a specimen up to 0.50" wide, and between 0.18" and 0.28" thick in the tabbed regions [9]. This is approximately the same as for the Wyoming-Modified Celanese test fixture. The standard 5.5" length defined for the IITRI and Celanese specimens

in ASTM Standard D 3410 [1] has been maintained, as has the 0.50" gage length. A schematic drawing and a photograph of an actual fixture are shown in Figure 25 [9,36]. This fixture weighs 23 lb, which is about one-fourth that of the standard IITRI fixture [37,38]. Of course, its specimen size capacity is correspondingly reduced relative to the standard IITRI fixture.

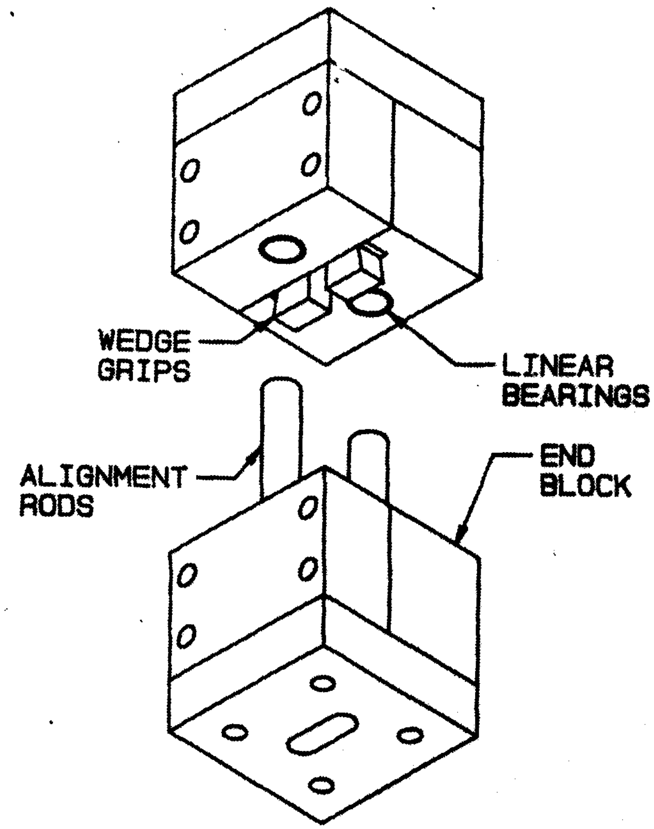
Each end block of the Wyoming-Modified IITRI fixture is fabricated in three pieces rather than the two pieces of the IITRI fixture shown previously in Figures 16 and 17. This permits the wedge grip cavity, which is totally contained in one of the two pieces, to be machined more readily since it is open. The mating cover piece is then pinned and bolted in place to close the cavity. The wedge surfaces of the cavity are thus integral with the end block, rather than being separate wedge pieces as in the standard IITRI fixture. The wedge grips are not bolted together in pairs as in the standard IITRI fixture, because they are only 0.50" wide and there is no space for bolt holes. Rather, there is a threaded hole in the inner (small) end of each wedge, to accommodate a countersunk socket head screw inserted from the end plate. The screw in each wedge grip is then used to draw up the wedge grips when the specimen is being installed, both to hold the specimen in position and to permit a clamping force to be applied to set the grips so that the specimen does not slip when the testing machine loading is initially being applied. Secondarily, these screws also retain the wedges in the fixture cavity between tests.

It will be noted that this method of gripping the specimen is essentially the same as used with the Wyoming-Modified Celanese test fixture. In the Wyoming-Modified IITRI fixture, however, the mating wedge surfaces are flat (as with the standard IITRI fixture) rather than cylindrical, and a full-length (5.5" long) specimen is used.

The 0.50" diameter posts and linear bearings used to maintain alignment between the fixture halves are also the same diameter as those used with the Wyoming-Modified Celanese fixture.

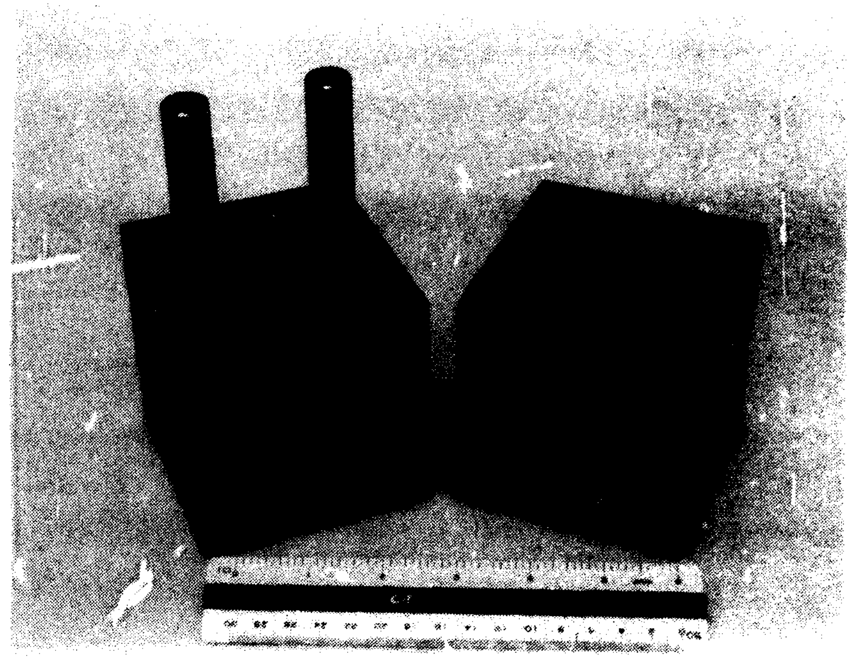
Stress States and Failure Modes

As for the Celanese, Wyoming-Modified Celanese, and IITRI compression tests, and all other methods relying on shear to transfer the load from the testing machine through fixture grips into the specimen, typically via tabs, there is a stress concentration induced in the test



WYOMING-MODIFIED IITRI
COMPRESSION TEST FIXTURE

Schematic of Fixture



Photograph of Actual Fixture

Figure 25. Wyoming-Modified IITRI Compression Test Fixture

specimen due to the discontinuity in the region at the end of the gage length where the tab begins. This was discussed in detail with respect to the Celanese test method above, and thus need not be repeated here.

Because of the stress concentrations present at the tab ends, failures commonly occur at, or even slightly inside the tabs [36], just as for the other test methods. Correspondingly, the failure modes are very similar. Typical failures obtained using these types of fixtures were previously shown in Figures 3, 12 through 15, and 20 through 22.

As for all of the other shear-loaded and end-loaded compression test methods, the compressive stress is simply the applied force at failure divided by the cross-sectional area of the gage section of the specimen, i.e., $\sigma = P/A$.

Although the physical size of the Wyoming-Modified IITRI test fixture is smaller than that of the standard IITRI fixture, it is still large enough so that the 1/2" to 1" of space between the upper and lower grip holders (depending upon how much each wedge grip is protruding from the holders) still makes it difficult to use an extensometer on the test specimen. It can be done but the reach distance is undesirably large [6]. Thus it is more practical to use a strain gage to measure strains, just as for the standard IITRI fixture.

As with any compression test, whenever there is any concern about specimen bending or buckling, it is necessary to use two strain readings to determine whether bending or buckling is present, as previously discussed in detail with respect to the Celanese compression test method.

Other Requirements and Modifications

Because of the use of flat tapered wedge grips, the thickness of the specimen in the tabbed regions is not fixed. Using the aggressive serrated wedge grip faces supplied as standard with the fixture [9], rather than the much smoother flame sprayed faces, is often an advantage also as the aggressive grips dig into the tab surfaces, helping to negate any local surface irregularities.

As in most cases, the precision of the fixture is critical to the success of the Wyoming-Modified IITRI compression test method [36]. The tapered flat surfaces of the hardened tool steel wedge grips must mate properly with their holders [25,26], and a high quality finish on these mating surfaces is important also. This cannot occur unless the individual components

are very accurately machined. For example, a high spot on one of the mating surfaces between the wedge grip and the spacer wedge it is sliding on can result in that wedge abruptly hanging up as the compressive loading is being applied. This will induce a strong bending moment in the specimen, as discussed previously with respect to the standard IITRI fixture [25,26].

Good alignment between the grips is maintained in the Wyoming-Modified IITRI fixture by the two 0.50" diameter hardened steel posts with linear ball bearings. This, in combination with the good rigidity of the fixture, and the recommended use of a spherical seat in the load train [1], makes the test fixture relatively forgiving of testing machine misalignments. As a result, scatter of the data reported in the literature for the Wyoming-Modified IITRI compression test method is at least as low as that obtained using any of the other compression test methods [36].

In summary, it is possible to measure compressive strength and modulus at least as accurately with the Wyoming-Modified IITRI compression test method as with any competing method. The flat wedge grips are a potential advantage relative to the tapered cylindrical wedge grips of the Wyoming-Modified Celanese test fixture, in terms of fit and therefore stability. On the other hand, the Wyoming-Modified Celanese compression test fixture has been used by a considerable number of testing laboratories during the past five years, with no problems reported. The Wyoming-Modified IITRI fixture does "look like" IITRI fixture, which is an ASTM standard, and since the IITRI fixture is generally considered to be much better than the Celanese fixture, this is a perceived advantage. However, the Wyoming-Modified IITRI fixture weighs more than twice as much as the Wyoming-Modified Celanese fixture, a handling disadvantage, and it also costs more than twice as much [9,37,38]. Thus, on balance, the Wyoming-Modified Celanese test fixture does seem to be the better choice of the two.

3.2 END-LOADED COMPRESSION TEST SPECIMENS

3.2.1 ASTM D 695 Compression Test Method

General Description of the Test Method

As the title of this ASTM Standard D 695, "Compressive Properties of Rigid Plastics" [30] implies, this test method was originally intended for compression testing unreinforced plastics. The method became an ASTM standard in 1942, before there was even much concern with determining the compressive properties of composite materials. In fact, there was not much concern with composite materials in 1942. The ASTM standard actually defines two types of test specimens and their corresponding fixtures. One is a simple cylinder of the test material loaded directly on its ends by flat platens. This configuration will be discussed in the subsequent section, "Block Compression Test Methods." This configuration is seldom used anymore by the composite materials testing community, as will be discussed later. Thus, when ASTM D 695 is mentioned in the context of testing composite materials, the second type of specimen and associated fixture defined in this standard is usually immediately assumed. This fixture and specimen are shown schematically in Figure 26. The fixture consists simply of two of these I-shaped lateral supports. They are held together by four bolts, one through each of the four projecting arms, with the test specimen sandwiched in between. It will be noted that the 3.13" long specimen is 0.25" longer than the 2.875" long lateral supports. The assembly is placed upright between flat loading platens of a testing machine and a compressive load applied directly to the ends of the specimen. There is no special provision for holding the assembly perpendicular to the loading platens.

The specimen is dog-boned as shown in Figure 26, the enlarged ends being provided to increase the bearing area and hence eliminate end crushing. For homogeneous, isotropic materials such as plastics this is adequate. For low strength, quasi-isotropic composite materials, e.g., random fiber-reinforced composites and quasi-isotropic laminates, and possibly even fabric-reinforced composites which exhibit a low orthotropy ratio, this configuration may still be adequate. However, for highly anisotropic (orthotropic) composite materials, certainly unidirectional composites and usually even [0/90] cross-ply laminates, it is not. Because the (ply) shear strength and transverse tensile strength of these materials is low relative to the

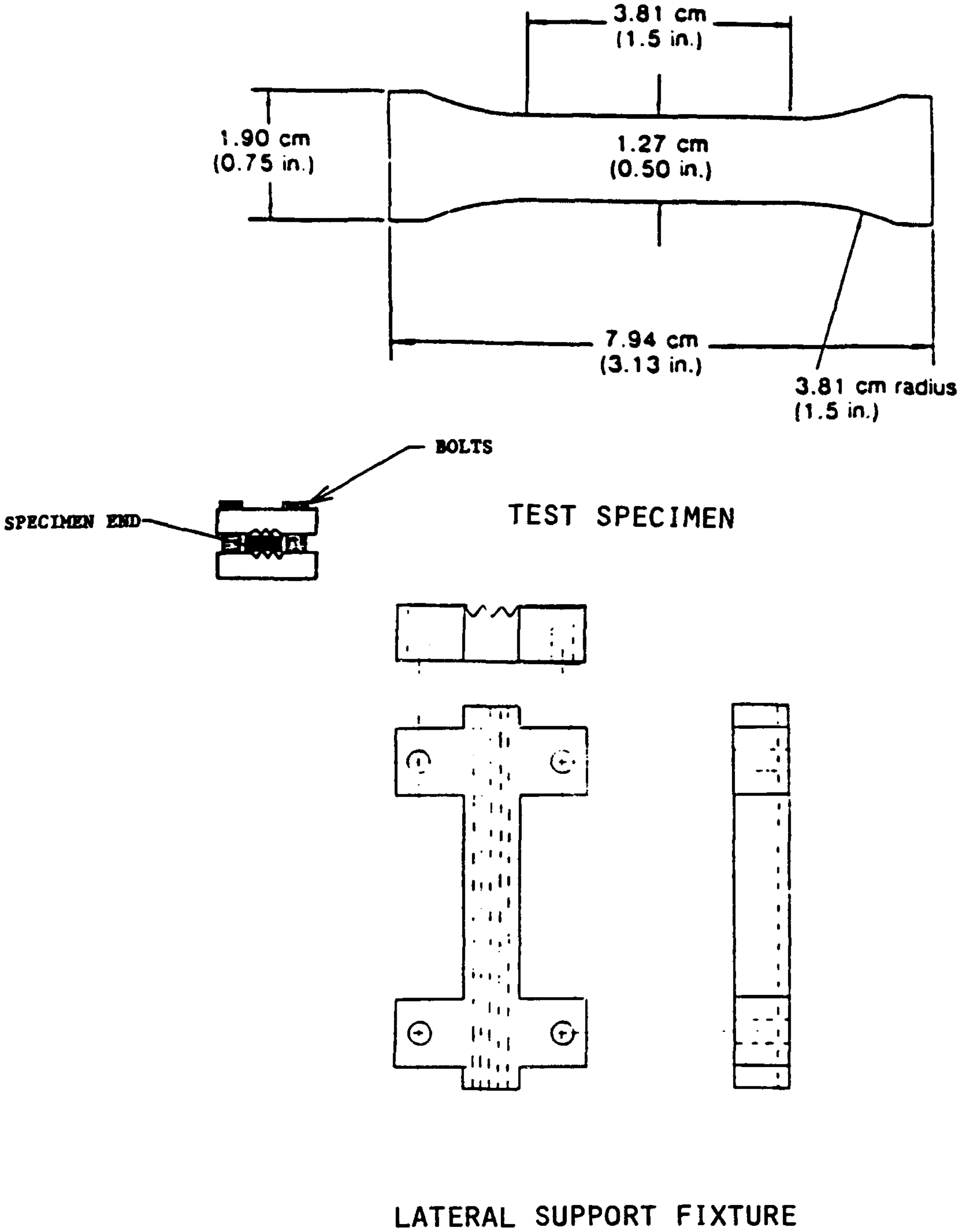


Figure 26. ASTM D 695 Compression Test Method [30]

compressive strength, longitudinal splitting and end-brooming will typically occur. Or splitting off of the dog-boned ends in line with the gage section width will occur, resulting in a specimen end of reduced bearing area, which will then crush and broom.

Thus, while the ASTM Standard D 695 test method [30] could be used for some composites compression testing, it is not always possible to predict when it will break down. Therefore, the composites testing community has looked to alternative methods and this method is not normally used at all.

Stress States and Failure Modes

Because of the transition in width from the constant (0.50") wide gage section to the 0.75" wide ends, there will be a stress concentration induced. Because the transition is gradual, this stress concentration should be relatively small. In most cases the naturally occurring stress concentrations due to material defects and/or machining will be greater, resulting in failures occurring randomly along the specimen. If this is the case, it can be assumed that a valid set of tests have been conducted.

Buckling should not occur because of the presence of the very stiff lateral supports. However, since both faces of the specimen are totally covered by the lateral supports, it is not possible to use strain gages or extensometers to check for buckling. It will be noted that the lateral supports are deliberately made slightly (0.063") narrower than the specimen itself. Thus, an extensometer can be mounted on the edge, if desired, to measure strains, and to permit the determination of a compressive modulus. However, any buckling that would occur would be out of the plane of the specimen, and not in the inplane direction that an edge-mounted extensometer (or extensometers) would detect.

If a valid test is performed, the failure modes obtained will be similar to those resulting from any of the other compression test methods. Since it is known that only low strength composite materials can be successfully tested using this method, as discussed above, and low strength composites are usually relatively easy to test, obtaining valid failure modes is usually not a problem.

Other Requirements and Modifications

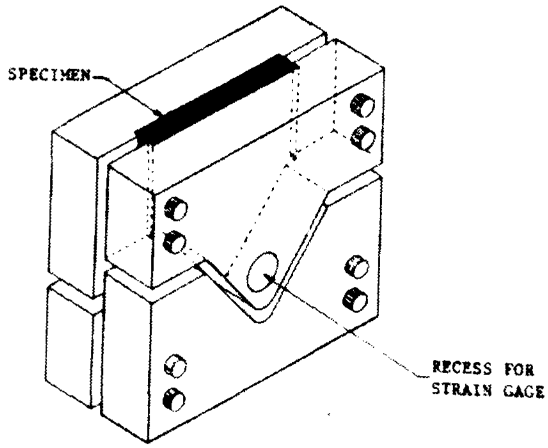
There have been a number of modifications of this ASTM Standard test method over the years. However, only the Modified D 695 Compression Test Method to be discussed in the next section, which has only been in existence since 1979 [25], and only known extensively for the past few years [42], is in common use at the present time. A few of the other configurations that have come and gone over the years are shown in Figure 27.

3.2.2 Modified ASTM D 695 Compression Test Method

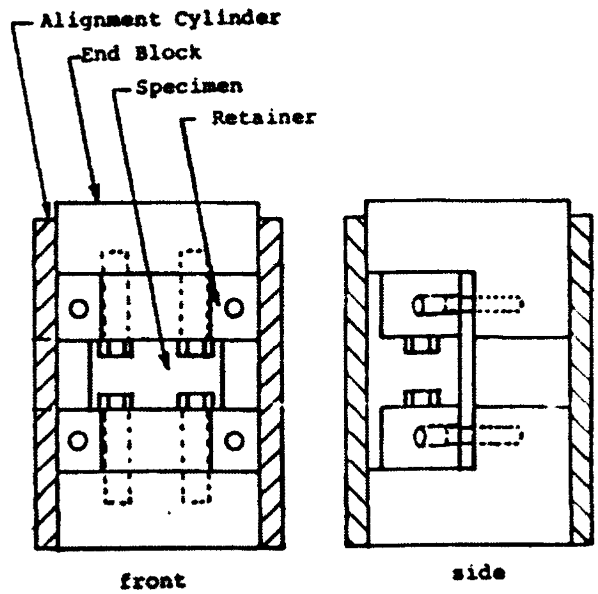
General Description of the Test Method

This modification of the ASTM Standard D 695 compression test method [30] discussed in the previous section is usually attributed to the Boeing Corporation [9,25]. It is probable that Hercules, Inc., and possibly other industry groups in the United States, also were involved in its original development during the late 1970's. However, it was Boeing that included it in their widely circulated Boeing Specification Support Standard BSS 7260, first issued in February 1982 [42]. Thus, it came to be commonly called the Boeing-Modified D 695 Compression Test Method [9,10,25,26,37,38]. That term will not be used here because the Boeing version has now been adopted by SACMA also, as Recommended Method SRM 1-88 [43], and is often referred to as such. In addition, this method is currently also being considered for adoption by the ASTM D-30 Committee.

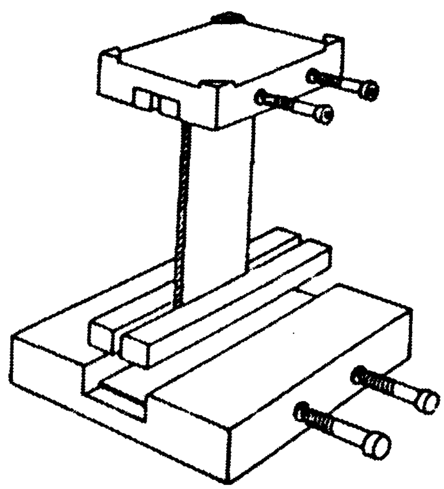
Schematics of the Modified ASTM D 695 Compression Test Fixture and corresponding test specimen are shown in Figure 28, and photographs of an actual test fixture and a tabbed compressive strength specimen is shown in Figure 29. As described in both the Boeing Standard [43] and the SACMA Recommended Method [43], two specimens are to be actually tested, viz., an untabbed specimen for determining the compressive modulus of the test material and a tabbed specimen for measuring the compressive strength. The standard specimen is 3.18" long and 0.50" wide, and of somewhat arbitrary thickness, although a relatively thin specimen on the order of 0.040" thick is commonly used. A thin specimen can be used since the untabbed specimen is supported against buckling along its entire length and the tabbed specimen has a very short gage length. Incidently, the Modified D 695 specimen



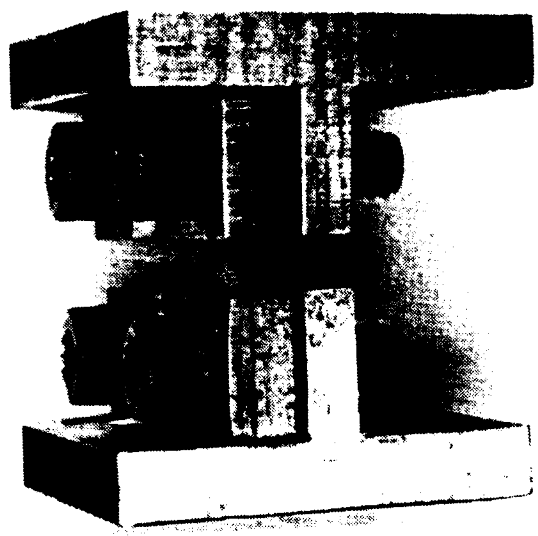
Northrop Compression Test Fixture [25]



NASA End-Loaded Compression Test Fixture [39]



Narmco Compression Test Fixture [21]



Convair Compression Test Fixture

Figure 27. Examples of End-Loaded Compression Test Fixtures

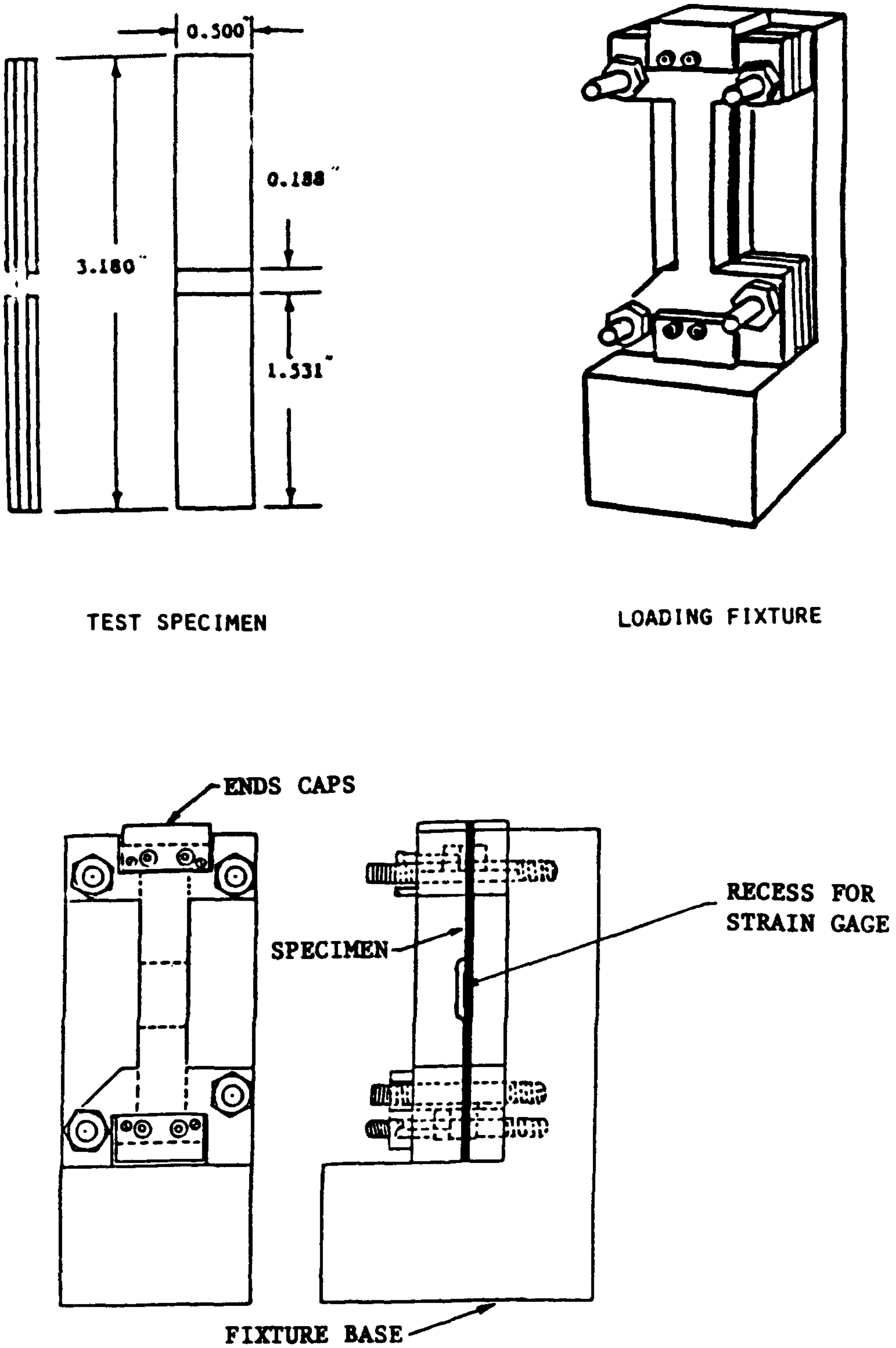
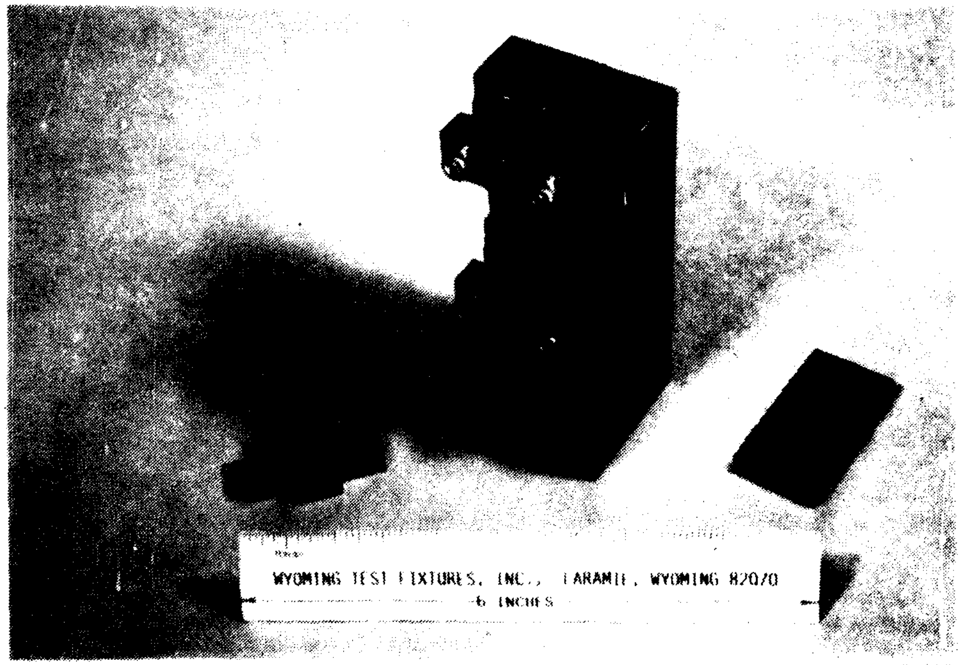
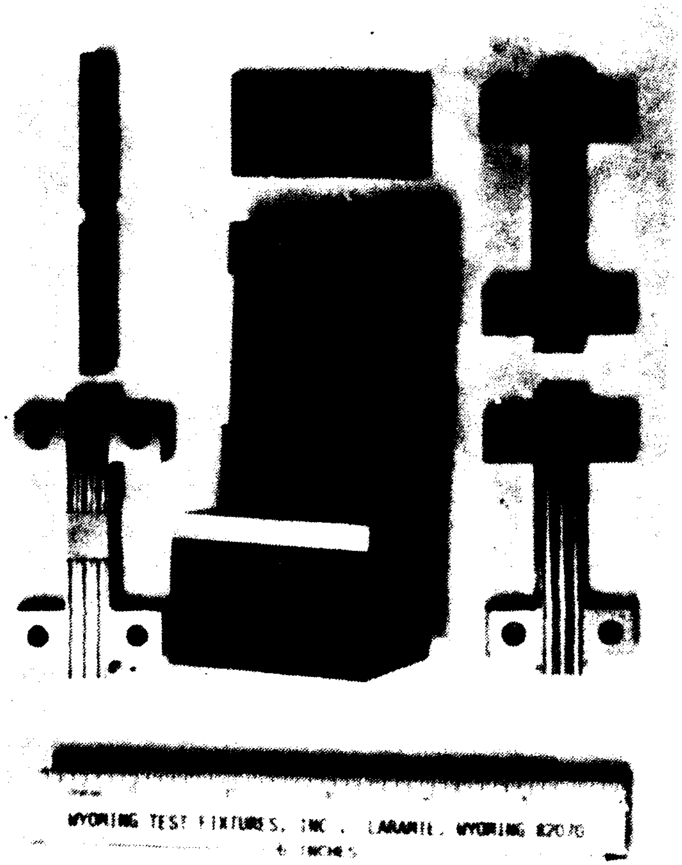


Figure 28. Sketches of Modified D 695 Compression Test Fixture and Specimen



Fixture Assembled for a Compressive Strength Test



Disassembled Fixture

Figure 29. Photographs of Modified ASTM D 695 Compression Test Fixture [9]

is 0.050" longer than the 3.13" long specimen defined in the ASTM Standard D 695 [30]. The reason for this is not clear, and the slightly greater length is probably not significant.

It will be noted from the photographs of Figure 29 that three essentially identical lateral support pieces are provided [9]. All three have deep axial grooves machined in the surface that contacts the test specimen. However, one of the three has these grooves machined away in its central 0.50" region, so that the lateral support piece does not contact the specimen there.

To determine compressive strength, the two continuous-groove lateral supports are used, with a tabbed specimen. Typically untapered tabs are used, with a very short (0.188") gage length (distance between tabs) [42,43]. This very short gage length was probably established to be consistent from a buckling standpoint with the relatively thin (0.040" thick) specimen typically used. However, it is too short to permit the use of strain measuring instrumentation. An extensive discussion of tab materials and geometries was presented previously for the Celanese Compression Test Method. Much of that information applies to the present case also. There are also some significant differences, however. Since essentially all of the load is applied to the specimen through its ends (there is some uncontrolled amount of frictional force between the specimen and the lateral supports), the bearing area at the specimen ends must be sufficient to prevent end crushing and brooming. Thus, the purpose here of the tabs is to increase this end bearing area. If the tabs are too thin, too compliant, or too low in strength, it is obvious that they will not perform adequately. However, if the tabs are too thick or too stiff relative to the specimen thickness and stiffness (they can never be too strong), then they will attempt to carry a higher percentage of the total applied load than the adhesive can shear-transfer into the test material and the tabs will shear off at the adhesive bond line. Once this happens, the specimen is back to an untabbed configuration and it will end crush prematurely. Thus, to achieve optimum performance, the tabs must be tailored to the specific composite being tested. Fortunately, it is often not necessary to achieve optimum performance, and a reasonable tab configuration will perform adequately. Thus, it is common to use standard tabbing materials, e.g., the 1/16" thick glass-fabric/epoxy composite printed circuit board material referred to earlier. However, it must be kept in mind that, when this does not perform adequately and end crushing or tab debonding becomes a problem, there are potential solutions readily available.

To determine modulus, an untabbed specimen is installed in the fixture using the lateral support with the cutout, plus one of the two continuous-groove supports. That is, there is a 0.50" unsupported length on one side of the specimen in its central region. This is to provide clearance for a strain gage bonded to the surface of the specimen. Alternatively, the two continuous-groove lateral supports could be used, with an extensometer attached to the edge of the specimen. As for the ASTM Standard D 695 test method [30], the lateral supports are slightly narrower than the specimen itself, to permit this. The specimen is loaded to a minimum strain of 0.3 percent, using either a strain gage or an extensometer to measure strain. From this information a compressive modulus can be calculated. If the loading were continued to higher levels in an attempt to determine the compressive strength also, the ends of the straight-sided, untabbed specimen would presumably crush prematurely, as discussed in detail in the preceding section, negating the strength test.

This need to perform two tests, on two different specimens, to obtain a set of data normally obtained from one test of one specimen is a strong negative of the Modified D 695 Compression Test Method. In addition, a complete stress-strain curve to failure is not obtained. Such information is not only useful for analysis purposes, strain to failure is also thus not obtained.

Stress States and Failure Modes

Because of the direct end loading, a severe stress concentration is induced at each end of the test specimen. For the modulus determination specimen this is ignored as being adequately away from the central region where the compressive strains are being measured. Correspondingly, the use of tabs with the strength specimen hopefully forces the failure to the central untabbed region of the specimen, again sufficiently away from the ends.

Bending or buckling of the untabbed stiffness-measuring specimen should not occur because of the presence of the very stiff lateral supports, which completely support both faces of the specimen. However, any bending or buckling that might occur would be out of the plane of the specimen, and thus might be detected by careful observation while using one strain gage. Since the specimen is loaded only to a very low strain level during modulus measurement, buckling is not going to occur and significant level of bending may not be observed. However, there is some consideration at present of providing an additional lateral

support with a cutout, so that strain gages could be mounted on both surfaces of the untabbed specimen, if desired. If one or even two extensometers are used, because they must be mounted on the edges of the specimen rather than on the faces, they will not be useful in detecting bending or buckling since these will almost certainly occur out-of-plane and edge-mounted strain devices can detect only inplane bending or buckling.

If a valid strength test is performed, the failure modes obtained will be similar to those resulting from any of the other compression test methods, most of which utilize a 0.50" gage length, even though only a very short 0.188" gage length is used. As discussed in detail in Reference [10], there appears to be very little influence of gage length on either the measured compressive strength or the observed failure mode.

A plot showing the experimentally determined lack of influence of gage length on compressive strength is shown in Figure 30, taken directly from Reference [10]. In addition to IITRI data generated by the authors of Reference [10], IITRI data taken from Reference [11], and both IITRI and Modified D 695 data taken from Reference [12] are also plotted in Figure 30. As can be seen, there is no apparent influence of fixture type, and no influence of gage length, as long as the gage length is not so great relative to the specimen thickness that gross (Euler) buckling occurs.

Other Requirements and Modifications

This test method has not been actively used for very long, and many mostly unsubstantiated opinions still abound, both in the literature and in verbal discussions. Much criticism centers on the use of such a short gage length. Some investigators argue that this results in artificially high compressive strengths, because of the overlapping influences of the restraints induced by the tabs being in such close proximity. Others argue equally strongly that the overlapping stress concentrations from the tabs result in decreased compressive strengths for short gage length specimens [11]. The data presented in Figure 30 would suggest that neither argument is valid. The main contributor to this present confusion is probably the fact that the induced stress concentration effect from each tab end extends an unexpectedly short distance (only 0.05" to 0.10") into the gage section from each tab end, as was noted relative to the discussion of the Celanese Compression Test Method previously [12-14], and as will be presented and discussed in detail in the DETAILED REVIEW OF

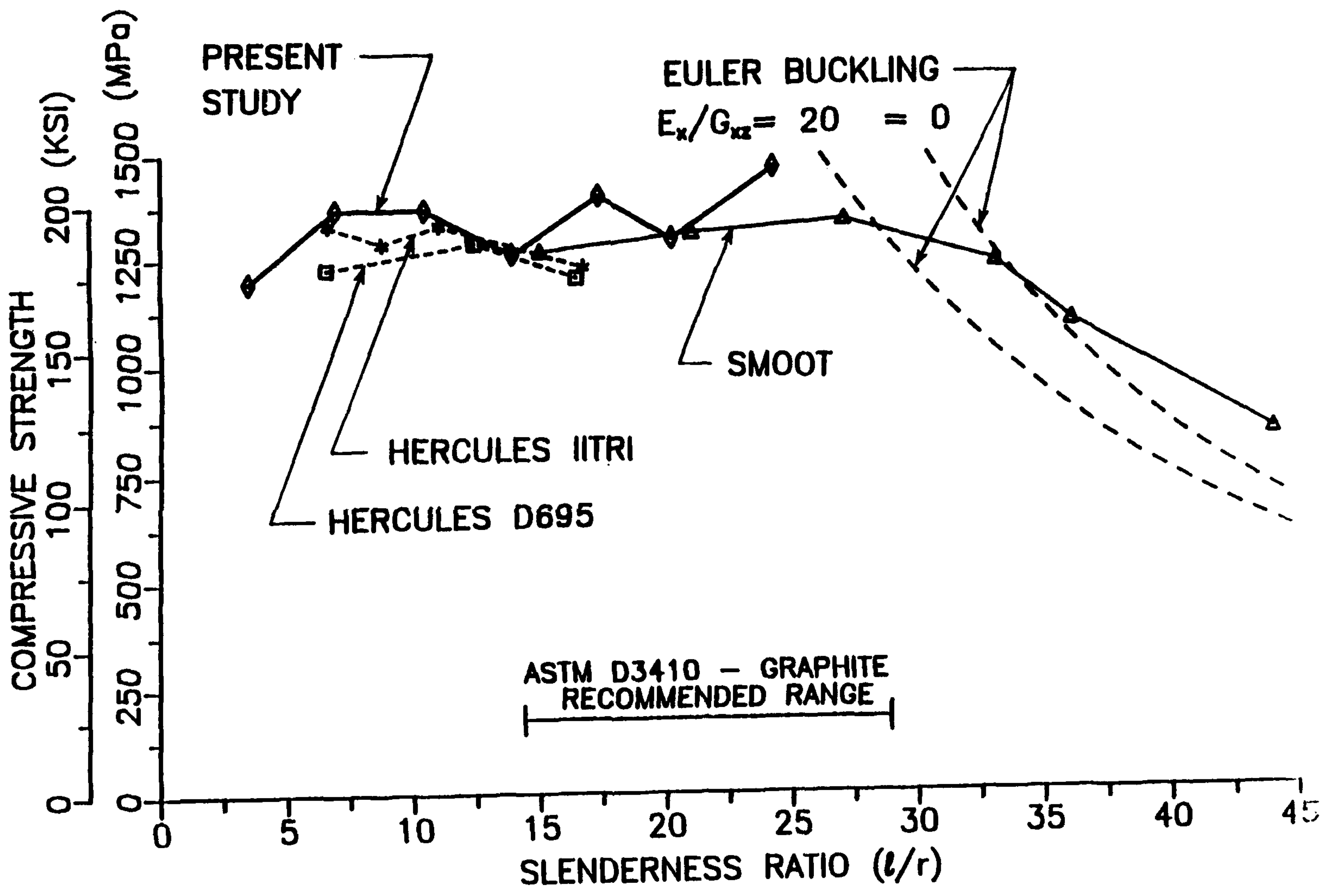


Figure 30. Compressive Strength of Various Unidirectional Carbon/Epoxy Composite Materials as a Function of Specimen Slenderness Ratio [10]

ANALYTICAL STUDIES section. That is, while the tabs themselves do potentially induce severe stress concentrations and hence reduce the apparent compressive strength, their effects do not influence the choice of specimen gage length.

3.2.3 Wyoming End-Loaded, Side-Supported (ELSS) Compression Test Method

General Description of the Test Method

The Wyoming End-Loaded, Side-Supported (ELSS) Compression Test Fixture has ben developed at the University of Wyoming over the past more than 10 years [25,26,35,37]. It was originally developed for use in both static and creep testing of low strength materials such as randomly oriented, short fiber composites [35]. In these cases an untabbed, straight-sided specimen loaded directly on its ends could typically be used.

A schematic drawing of the fixture is shown in Figure 31 and photographs of an actual fixture in Figure 32. The goal is simplicity, the fixture consisting of four essentially identical steel blocks held together in pairs by socket head cap screws. Slots down the center of each block, less than half of the thickness of the test specimen, are used to hold the specimen in alignment perpendicular to the ends of the blocks. The slots are only slightly wider than the specimen itself (typically about 0.005" wider). In use, the pairs of blocks are spaced apart a distance defining the specimen gage length.

It will be noted that the ELSS fixture uses alignment rods and linear ball bearings, just as the various shear-loaded specimen fixtures do. Here again, this is very effective in maintaining alignment between the fixture halves. The original version [35] of this fixture simply used alignment rods in machined holes in the blocks, and as discussed in detail in References [25,26] this sometimes resulted in binding and excessive friction. That is the fixture itself carried a portion of the applied force, causing the calculated compressive modulus to be anomalously high and the strength values to be erratic [25,26].

Because of the simplicity of the fixture design, it is not impractical to configure and fabricate a fixture for each individual test series, to match the specific specimen configuration it is desired to use. In fact, this has been done frequently at the University of Wyoming [6]. However, a standard fixture has also been developed [9]. It accommodates a specimen 5.5" long (the same as the IITRI and Celanese test methods) and 0.50" wide (a commonly used

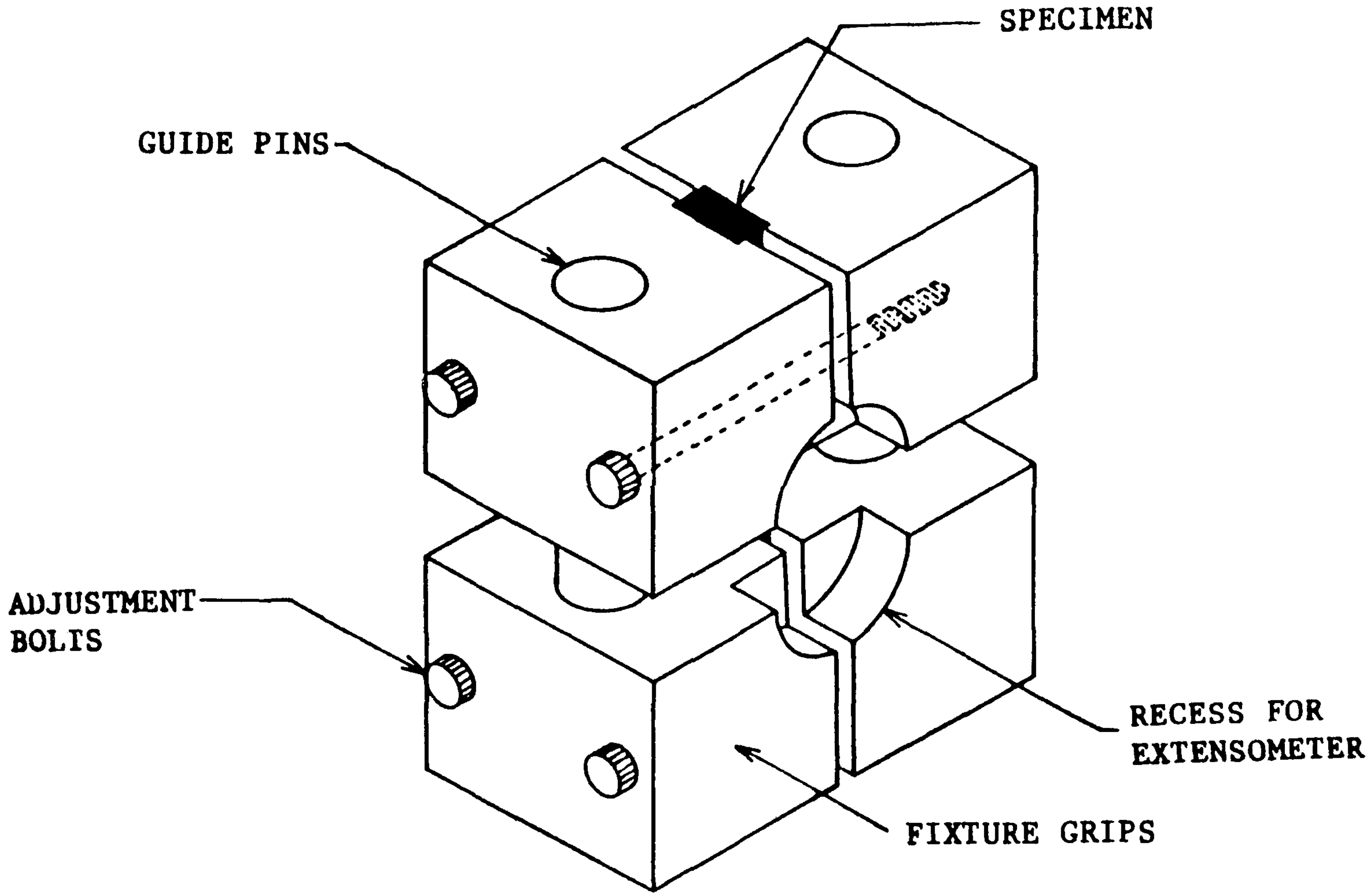
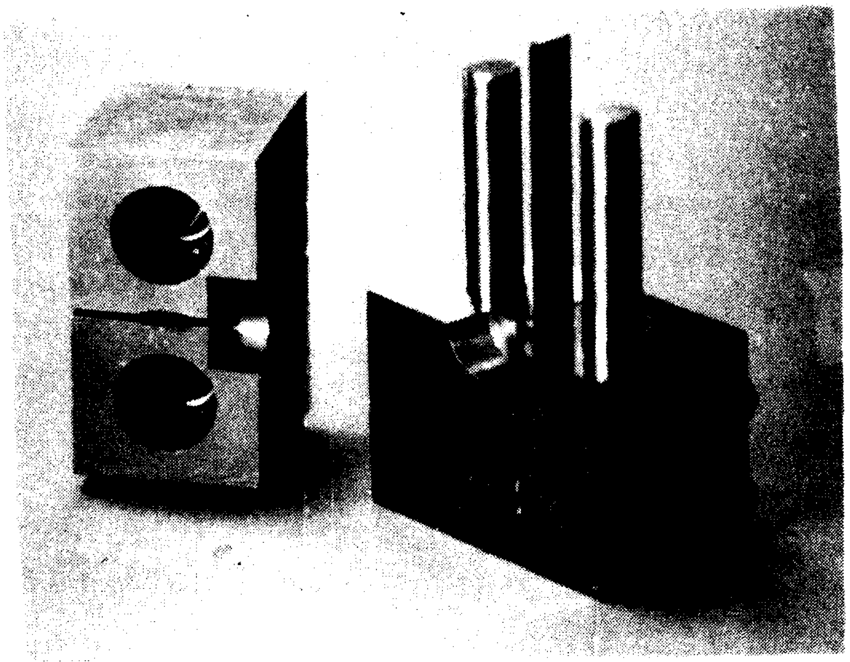
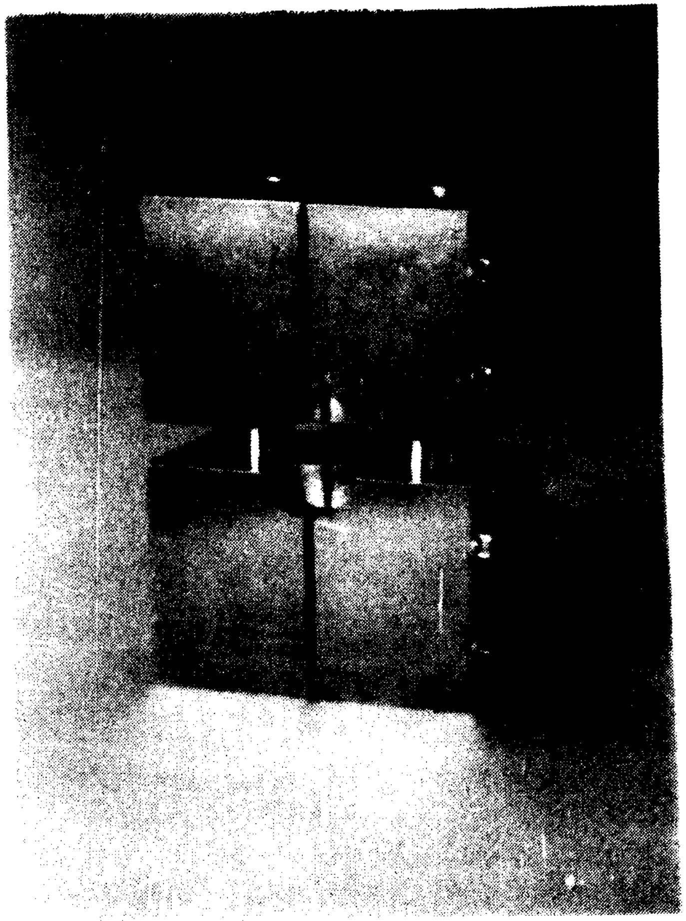


Figure 31. Schematic of Wyoming End-Loaded, Side-Supported Compression Test Fixture with Specimen Installed [25]



Specimen Installed in Lower Half



Assembled Fixture with Specimen Installed

Figure 32. Photographs of Wyoming End-Loaded, Side-Supported Compression Test Fixture [9]

width). The 2.50" long support blocks then form a 0.50" specimen gage length. Of course this can be readily varied by the user, by making the specimen longer or shorter.

Although specimen thickness can be arbitrary as long as it is greater than the thickness of the slot formed when two fixture halves are in contact (the standard fixture has a total slot thickness of 0.060" [9]), a specimen thickness of 0.100" is commonly used.

Stress States and Failure Modes

Because of the direct end loading, a severe stress concentration is induced at each end of the test specimen, just as for all end-loaded specimen test methods. However, because the gage length is well-removed from the ends, this is not a factor in determining either compressive strength or modulus.

Overall bending or buckling of the specimen should not occur because of the presence of the very stiff lateral supports. However, because the central portion (gage section) of the specimen is unsupported, bending and buckling can occur there, just as for any of the shear-loaded specimen test methods. Thus, the same precautions should be followed, as previously discussed.

The circular cutout in one face of the fixture, as indicated in Figures 31 and 32, is simply to provide additional clearance for the body of an extensometer if one is to be used to measure compressive strains. It will be noted that the extensometer is to be attached to the edge of the specimen. Of course, strain gages, on one or both faces of the specimen in the central gage length region, can also be used. The discussion of using strain gages versus extensometers is essentially the same as presented previously for the Modified ASTM D 695 Compression Test Fixture, except that in the present case there is no problem with the lateral supports interfering with the placement of the strain gages. Also here only one specimen is needed to determine both compressive strength and modulus, a distinct advantage.

If a valid test is performed, the failure modes obtained will be similar to those resulting from any of the other compression test methods, including the shear-loaded compression specimen test methods, most of which also utilize a 0.50" gage length. To demonstrate, typical failures of untabbed ELSS specimens of a randomly oriented, chopped glass fiber/polyester composite, i.e., a sheet molding compound (SMC) are shown in Figure 33 [6]. Although not shown in this photograph, there was no end crushing or specimen gross

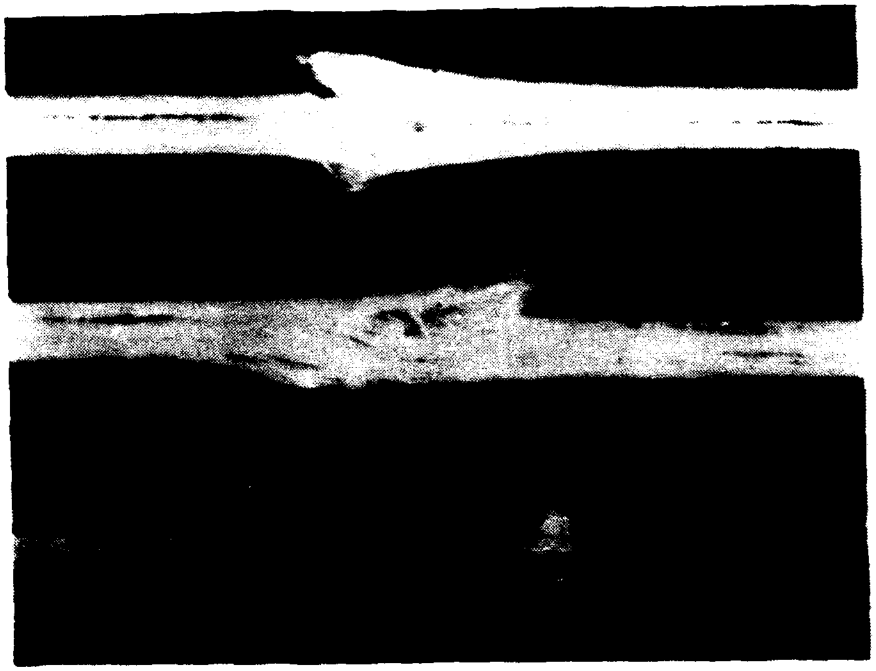


Figure 33. Failed Wyoming End-Loaded, Side-Supported Compression Test Specimens [6]

Upper Two Specimens: SMC-R65 Random Glass/Polyester Composite
Lower Specimen: Unidirectional E-Glass/Epoxy Composite

buckling. That is, a fully valid failure mode was obtained in all cases. However, these are relatively low strength materials. Shown in Figure 34 are untabbed, end-loaded specimens of medium and higher strength materials [25]. It will be noted that end crushing occurred for the unidirectional composites, while valid failures in the gage section were obtained for the quasi-isotropic (lower strength) laminates.

Other Requirements and Modifications

As noted above, the Wyoming End-Loaded, Side-Supported (ELSS) Compression Test Fixture was originally developed for use with low strength materials, where a straight-sided specimen without tabs could be used [35]. In fact, it has been very successfully used in many such applications over the past 10 years [25,26,35]. It has been found that for composite materials exhibiting compressive strengths in the range of 100 to 125 ksi or less,

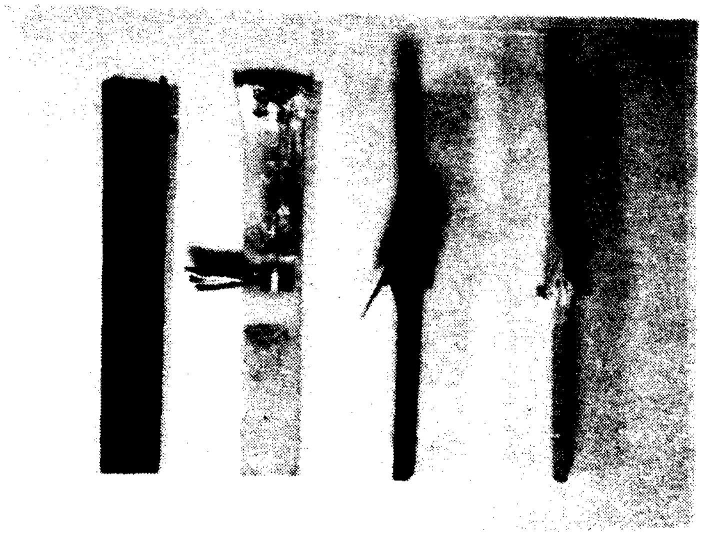


Figure 34. Typical Failures of Wyoming End-Loaded, Side-Supported Compression Test Specimens [25]

a) AS4/3501-6 $[0]_{16}$ Carbon/Epoxy
b) S2/3501-6 $[0]_{32}$ Glass/Epoxy
c) AS4/3501-6 $[45/0/-45/90]_{3s}$ Carbon/Epoxy
d) S2/3501-6 $[45/0/-45/90]_{4s}$ Glass/Epoxy

there is typically no problem with end crushing or brooming, and failures occur in the central 0.50" gage section of the specimen [25,26]. Also, the strengths and stiffnesses obtained are totally consistent with those obtained using any of the other compression test methods, including the IITRI. For higher strength materials, end failures begin to be a problem. The solution, of course, is to add end tabs to the specimen, maintaining the 0.50" gage length between tabs. In fact, the specimen is then identical to a 0.50" wide IITRI, Wyoming-Modified IITRI, or (if the specimen is made only 4.5" long) a Wyoming-Modified Celanese compression specimen, and it becomes a question of whether to just use one of these shear-loaded specimen test methods instead, since they are generally more readily accepted, and perhaps more reliable in terms of tab performance. The ELSS fixture is definitely easier to use however, since it only need be opened up enough to slip the test specimen down the slot, and

then the four screws retightened. In this regard the ELSS fixture is somewhat similar to the Modified D 695 test method [42,43].

The ELSS fixture was originally designed for the screws to be only lightly tightened, just enough for the lateral support blocks to restrain the specimen against buckling [35]. This remains the intention of the lateral support blocks. In fact, in the standard fixture [9], the fixture faces contacting the specimen are relatively smooth, being only grit blasted. However, it has been suggested [6] that it may be possible to carry a significant portion of the applied loading via shear through the lateral support blocks if they are tightened sufficiently against the specimen. They could then also be roughened considerably, perhaps by the flame spraying process previously discussed. In fact, it has been suggested that if on the order of 20 percent of the total applied force could be transferred via shear, it may be possible to use an untabbed specimen even when testing very strong materials [44]. As a result, there have been preliminary attempts to do so with the ELSS fixture [6]. To date, these very limited efforts have not been successful, but the potential benefit will make it well worth investigating additional effort.

Another area where additional work appears to be well-justified is in the potential use of face-tapering of untabbed specimens, i.e., machining the surfaces of the composite in the gage section to reduce the cross-sectional area. This would be limited to unidirectional composite materials unless a dummy material were cocured onto the surface of the laminate to be tested, to be machined through during the face-tapering operation. Otherwise, the nature of the laminate to be tested (the number and stacking sequence of the plies) would be altered by the face-tapering. Of course, this would not be impractical to do, and in fact has been tried [31,45].

The problem has been is that face-tapering has not been generally accepted in the past by the composites community. The usual concern is that the nature of the as-fabricated composite is altered if the surface plies are removed. In fact, the Royal Aircraft Establishment (RAE) test method [46] is one of the very few methods ever proposed that incorporates face-tapering, and it is not used at all in the United States, and only to a very limited extent in Europe, primarily in England where it was originally developed [40,46,47]. However, because of the difficulties the composites community has been made aware of in attempting to compression test the high strength, highly orthotropic composites during the past several years, it may be necessary to rethink this attitude. The advantage of face-tapering is primarily

for end-loaded specimens rather than shear-loaded specimens since the full bearing area at the ends of the specimen can be retained while the cross-sectional area of the gage section is reduced, thus requiring less force to fail the specimen. Of course, the end-loaded specimen can be edge-tapered instead, to achieve a similar goal, and this has been tried [6,48,49], but with little success. The problem is that edge-tapering of unidirectional composites tends to induce shear failures up into the enlarged ends, parallel to the sides of the gage section. That is, the dog-boned specimen partially or fully reverts to a straight-sided specimen during the test, with a corresponding reduction in end-bearing area, resulting in end crushing and brooming. When face-tapering is used, the shear area presented to the potential tab crack is much larger, being equal to the specimen width times the length of the dog bone end rather than equal to the specimen thickness times the length of the dog bone end. For example, if the gage section of the specimen were to be 0.50" wide and 0.10" thick (typical dimensions), there would be a factor of five advantage of face-tapering. If the composite before face-tapering can be made even thicker, the advantage becomes proportionally greater. In contrast, there is no advantage in making the edge-tapered specimen either wider or thicker. Wider dog bone ends only increase the shear transfer problem, and a thicker specimen increases the cross-sectional area in direct proportion to the increase in end-bearing area, with no net advantage.

The Wyoming End-Loaded, Side-Supported (ELSS) Compression Test Method can perhaps be considered as just one more modification of the original ASTM D 695 compression test method. Many others are noted at the conclusion of the discussion of the ASTM D 695 test method in an earlier section. There is one other modification that perhaps deserves special mention here, however. This is the extensive work by Camponeschi [50-52] to characterize the compressive properties of thick composites. He tested both unidirectional composites and cross-ply laminates of carbon/epoxy and glass/epoxy, up to 1" thick. His fixtures, each proportioned to the specimen thickness being tested, are similar in concept to the Wyoming ELSS fixture, without the alignment rods and linear ball bushings. Camponeschi did use tabs on all of his specimens. Thus, problems previously discussed here with respect to achieving the proper balance between tab material and thickness and specimen material and thickness were encountered, as discussed in his reports. Camponeschi also analyzed the stress state in the specimen due to the presence of the stiff lateral constraints, and the torque used to tighten them to the specimen prior to testing, and how this influenced the failure

modes actually observed [52]. His analytical work will be reviewed in detail in the DETAILED REVIEW OF ANALYTICAL STUDIES section of the present report.

Gürdal and Starbuck [53] designed an end-loading fixture which contained four circular side support pins to prevent out-of-plane displacement of the specimen. However, sufficient information about the performance of this fixture is not available to evaluate this fixture.

3.2.4 RAE (Royal Aircraft Establishment) Compression Test Method

General Description of the Test Method

In the above presentation of the Wyoming End-Loaded, Side-Supported (ELSS) Compression Test Fixture, a brief discussion was included of the possibility of transmitting a portion of the applied loading into the specimen via shear transfer through tightly clamped lateral support blocks. The stated purpose was to reduce the end loading sufficiently to eliminate specimen end crushing and brooming.

What has become to be known as the RAE Compression Test Method was developed at the Royal Aircraft Establishment in England in the early 1970's specifically to achieve this same goal. Port [40] correctly attributes the original development to Purslow and Collings [46], although an RAE Technical Report was published a year earlier by Ewins [47], describing the same RAE axial compression test method in detail. In fact, Ewins [47] acknowledged the forthcoming RAE report by Purslow and Collings in his discussion. Ewins [47] also presented the design of axial tensile and transverse tensile and transverse compressive specimen test methods as well, based upon similar principles.

In the RAE axial compression test method, an untabbed specimen is adhesively bonded into relatively deep and close fitting slots in end blocks twice as deep as the slot, and about 1.58" (40 mm) wide. The adhesive is presumed to carry a significant portion of the applied load. It has been stated [40] that on the order of half of the applied load is transmitted in this manner, although there does not appear to be any experimental or analytical proof of this.

The simple test configuration used is shown in Figure 35. It consists of two aluminum end fittings, each with a 0.59" (15 mm) deep, 0.090" (2.28 mm) wide, flat-bottomed slot machined across one surface. The specimen is 1.89" (48 mm) long, and thus the unsupported length is 0.71" (18 mm), and it is 0.079" (2.00 mm) thick at its ends. As also

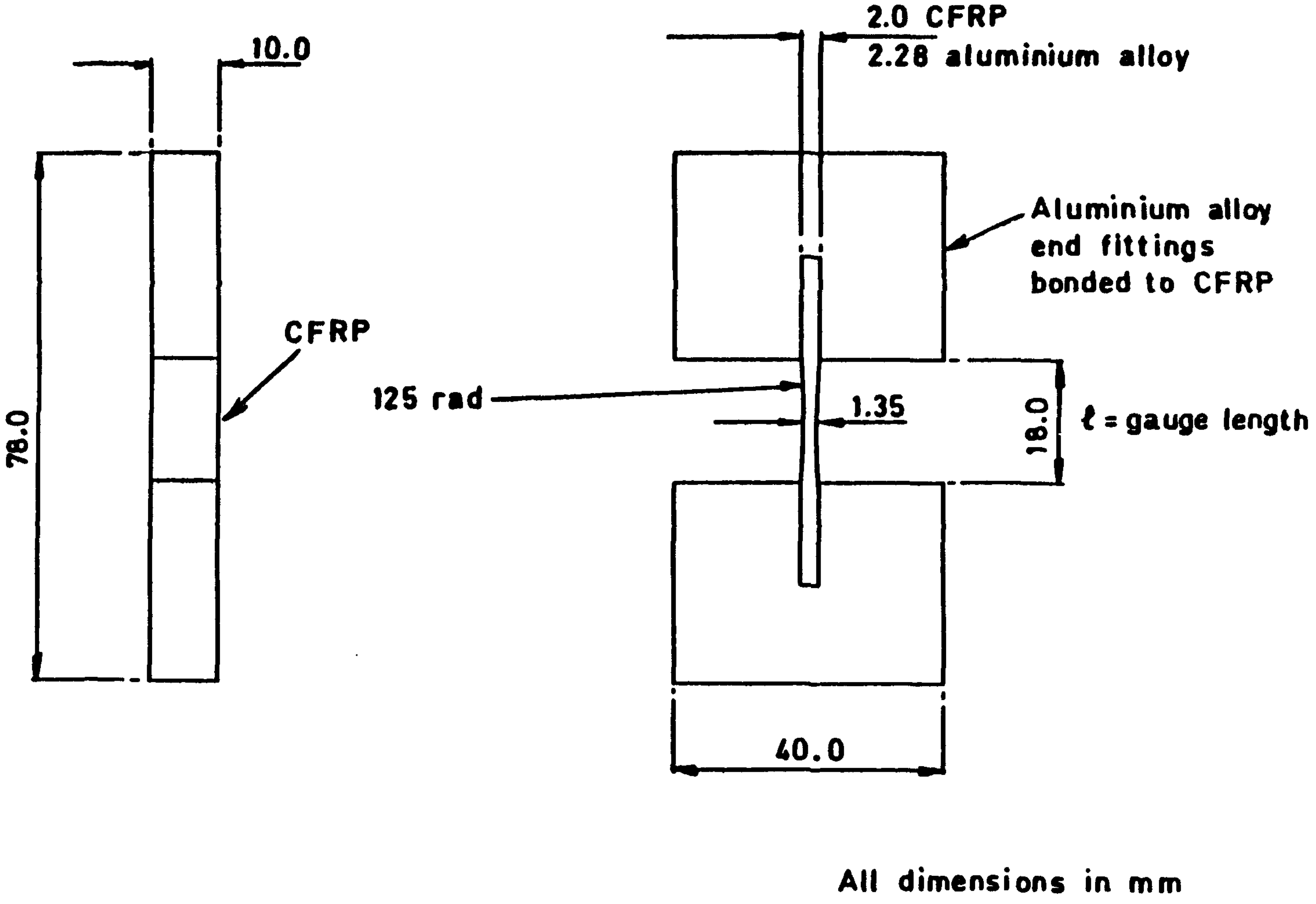


Figure 35. Schematic of Standard RAE Compression Test Specimen [40]

discussed previously with respect to the ELSS specimen, the RAE specimen is thickness-tapered, using a 4.9" (125 mm) continuous radius to reduce the mid-length of the specimen to 0.053" (1.35 mm). That is, there is no constant thickness gage section; the thickness continually varies along the gage length, being about two-thirds as thick at its minimum cross section as at its ends. The standard specimen is 0.39" (10 mm) wide, as are the end fittings. The justification for choosing this specimen configuration is presented in detail by both Ewins [47] and Port [40].

Port [40] presents results indicating the influence of slenderness ratio on the measured compressive strength of a unidirectional XAS carbon fiber-reinforced 914 epoxy (Ciba-Geigy). These slenderness ratio variations were obtained by varying the gage length between 7 and 25 mm, with the specimen thickness being held constant at 1.35 mm. The taper radius was varied accordingly, so that the reduced section still varied over the entire gage length. Port's results are presented in Figure 36. The data indicated for the Modified ASTM D 3410 specimen are for a thickness-tapered Celanese specimen of the configuration shown in Figure 37, tested in a standard Celanese Compression Test Fixture. The Euler buckling curve in Figure 36 is plotted for a simply supported end condition assumption, which is obviously not the condition for the RAE specimen (see, for example, the plot of Figure 30, previously discussed, for an indication of the influence of end constraint). Thus, the Euler curve shown is much too low. However, it will be noted, by looking only at the experimental data for the RAE type specimen, that the standard RAE configuration, incorporating an 18 mm gage length, appears to have failed by buckling. It further appears that a gage length of about 12 mm or less would be required to force a compressive failure rather than a bucking failure. Port [40] acknowledged this potential buckling problem. However, the gage length cannot be too short with the thickness-tapered RAE specimen, as the low value of compressive strength obtained for a gage length of 0.28" (7 mm) indicates. As predicted by Port's analysis [40], for very short gage lengths the shear stresses in the taper region become sufficiently large to cause shear failures along the length of the specimen in the enlarged ends, parallel to the specimen minimum thickness. Thus, the specimen is effectively converted to a straight-sided configuration, and end crushing occurs at the end blocks, leading to premature failures. The data for the "proposed new standard specimen" thus indicate the use of an RAE specimen with a 0.45" (11.5 mm) gage length rather than the standard 0.71" (18 mm) gage length, to avoid buckling. It will be recalled that all of the shear-loaded specimen compression

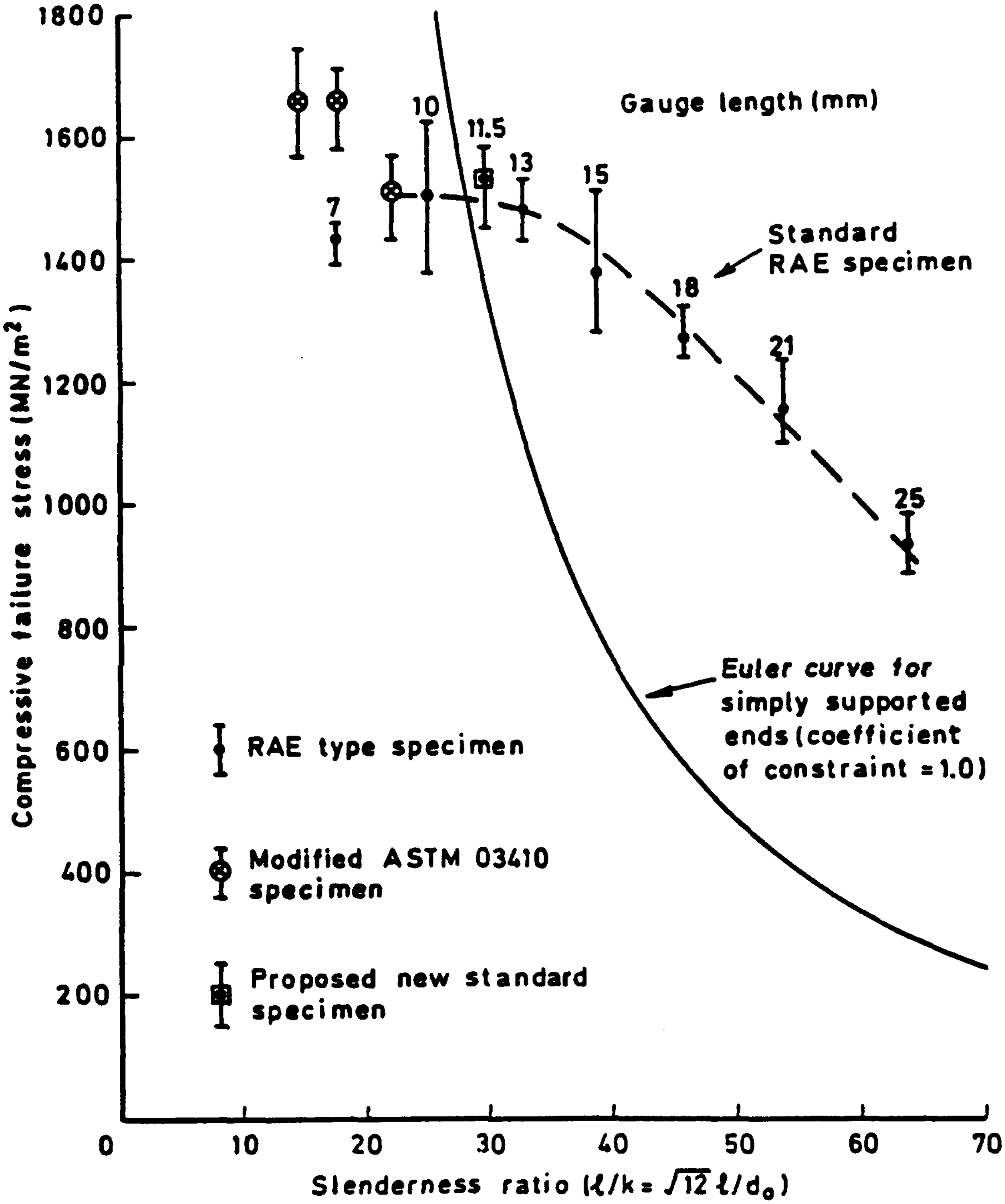


Figure 36. Variation of Compressive Strength with Slenderness Ratio for a Unidirectional Carbon/Epoxy Composite [40]

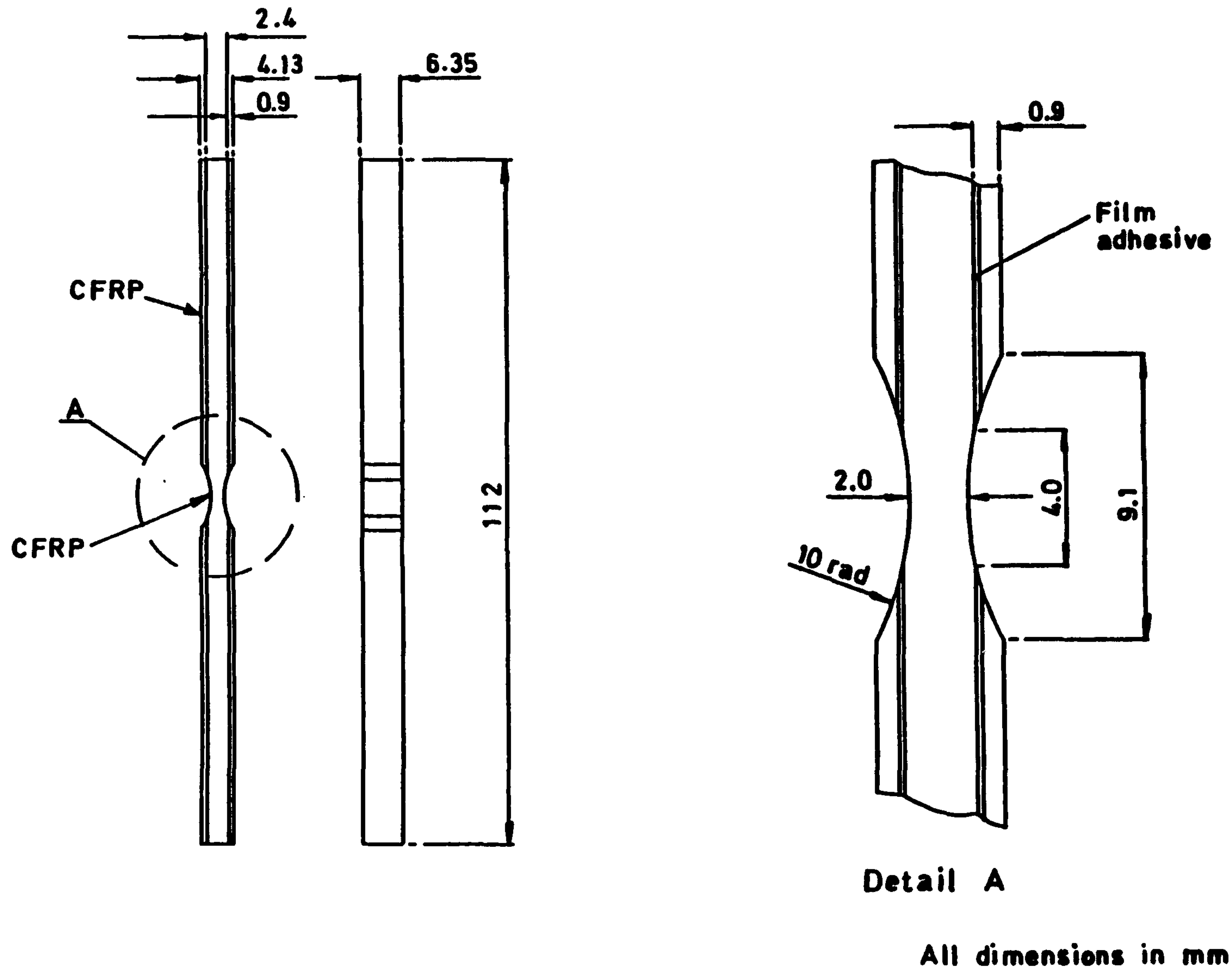


Figure 37. Schematic of Modified ASTM D 3410 Compression Test Specimen [40]

test methods previously discussed, i.e., the Celanese, Wyoming-Modified Celanese, IITRI, and Wyoming-Modified IITRI, and also the Wyoming End-Loaded, Side-Supported (ELSS) compression test method, all use a 0.50" gage length, which typically results in a slenderness ratio in the range of 15 to 30, depending on the specimen thickness.

It will be noted that the results for the Modified ASTM D 3410 (width-tapered Celanese) tests were higher than the RAE results. Woolstencroft, et al. [45] used three-dimensional NASTRAN MSC finite element analysis results to suggest that this was due to high transverse (through-the-thickness) compressive stresses induced in the test specimen at its mid-length that suppressed a buckling failure. A maximum compressive stress of 6.5 ksi (45 MPa) was predicted at the center of the specimen. The through-the-thickness compressive stresses induced in the RAE specimen were predicted to be negligible, i.e., 0.1 ksi (1 MPa). This conclusion needs to be verified, both experimentally and analytically. It may be that the Modified ASTM D 3410 (thickness-tapered Celanese) specimen configuration is simply inherently more stable against microbuckling than is the RAE specimen configuration.

Stress States and Failure Modes

The analysis of Woolstencroft, et al. [45] suggests that the axial compressive stress in the RAE specimen is very uniform across the minimum cross section. Thus, the compressive strength can be calculated simply as the applied axial force at failure divided by this minimum cross-sectional area.

Port [40] presents a detailed discussion of failure modes, defining them as Types A through D. Type A is the desired mode, a failure in the gage section at or very near to the minimum cross-sectional area. Type B is a failure at the point where the specimen emerges from an end block. Type C is the interlaminar shear failure referred to above when the gage length becomes too short, reducing the specimen to effectively a straight-sided specimen. Type D is a mixed mode failure, where considerable interlaminar splitting is evident even though the primary failure is at, or close to, the minimum cross section. Port [40] tabulates the percentage of specimens failing in each of these modes for each of the slenderness ratios he tested. For example, 83 percent of the failures were Type C and 17 percent Type B for the tests of the 7 mm gage length, whereas for the 10 mm gage length, 67 percent were Type B, 25 percent Type A, and only 8 percent Type C (see Figure 36). Unfortunately,

Type B failures ar not desirable. Interestingly, 100 percent of the failures of the 18 mm gage length standard RAE specimens (5 specimens) were Type A, the only desirable failure mode. Unfortunately again, these specimens appear to have buckled, as indicated in Figure 36. The majority of the other specimens having gage lengths greater than 18 mm also exhibited Type A failures, the remainder being Type D. In summary, the specimens that did not buckle failed primarily at the end fittings, or at the ends due to longitudinal splitting.

Reference [54] is a very recent attempt to apply a number of the standard failure criteria, e.g, maximum stress, Tsai-Hill, Hoffman, Tsai-Wu, Hashin-Rotem, Strain Energy Release Rate, in predicting the failure of thickness-tapered compression specimens. Experimental data were generated for three specimen geometries, using a unidirectional E-glass/F913 epoxy (Ciba-Geigy) composite material. A linear elastic, plane stress analysis was performed using the ABAQUS finite element computer program. The results obtained were not conclusive.

Other Requirements and Modifications

It will be important to analytically determine how much of the applied compressive load is actually transmitted to the RAE specimen by the adhesive in a shear-loading mode. The available experimental results discussed above suggest that it may be a relatively high percentage of the total in the standard RAE specimen configuration. Once this is determined, it will be possible to optimize the specimen geometry. At present the failure modes observed are not acceptable, being either buckling or end crushing.

One issue that has not been addressed in any of the cited publications is how the failed specimen is removed from the end blocks. It may be that the end blocks are considered to be single use items. This would not be cost prohibitive, but certainly unattractive relative to all of the fully reusable fixtures.

3.2.5 Block Compression Test Methods

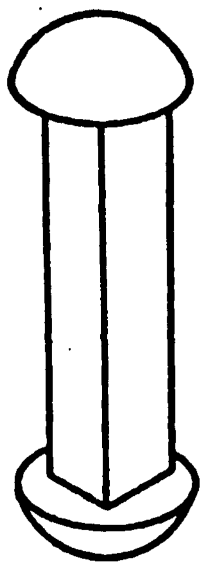
General Description of the Test Method

There are a variety of compression test methods in this class. The most basic procedure is to load a cube or short column of the composite material between parallel flat platens. This

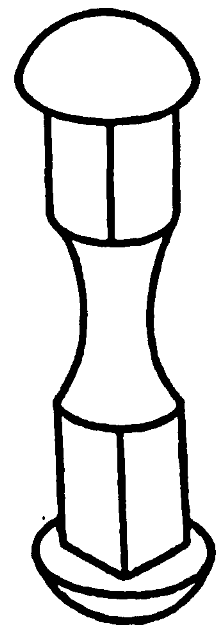
simple approach has long been used for compression testing of metals, and thus was a logical first attempt when testing fiber-reinforced composites. However, for composite materials end crushing is a dominant problem, just as previously discussed with respect to other direct end-loading test methods such as the ASTM D 695 [30] and ELSS [9,25,26,35,37] test methods. Thus, extensive studies have been performed over the years in an attempt to devise a suitable end reinforcement configuration. (See, for example, the literature reviews in References [25,27,50]. Since by the definition used in the present report these block specimens are not laterally supported, except possibly just near each end, buckling is always a problem to be avoided. Thus, an adequately thick composite must be available for testing. This in itself is often a major limitation in using this class of test methods, as most of the other material property tests permit the use of thinner materials, and thus that is all that may be available for use.

It will be recalled from the previous discussion that ASTM Standard D 695 [30] actually describes two compression test methods, one of which has already been presented in detail. The other method described in the ASTM standard is to directly end load a short column of the composite material (or unreinforced plastic). During the early development of such compression testing methods, work proceeded concurrently in the United States and Europe. Boron fibers were a promising new reinforcing material at that time (the mid- and late-1960's), exhibiting very high unidirectional composite compressive as well as tensile strengths, and Texaco Corporation in the United States was a leading producer of boron fibers. Thus, Texaco developed a compression test configuration whereby the block specimen was capped with hardened steel hemispheres bonded to its ends, as shown in Figure 38a [55]. The hemispheres were to assure a uniform uniaxial loading state and to minimize induced bending. But strain gages mounted on opposite sides of the specimen indicated that eccentric loadings could still be induced. Based upon these results, Weidner [56] at the University of Dayton Research Institute (UDRI) later designed the UDRI specimen. He started with the Texaco configuration, aligning the specimen axis in a lathe. He then waisted the specimen in the gage section (see Figure 38b), the reduction in cross-sectional area promoting failure in that region. He obtained higher strengths than with the Texaco specimen, but a large amount of data scatter was noted.

Meanwhile in Europe, research was also being conducted on block-type specimens. Ewins [57] at the Royal Aircraft Establishment (RAE) in England followed an approach similar



a) Texaco Short Column Compression Test Specimen



b) University of Dayton Research Institute (UDRI) Compression Test Specimen

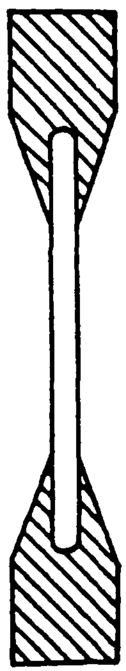
Figure 38. Typical Short Column Compression Test Specimens [56]

to that noted above. Initially he capped the ends of his cylindrical rod specimens in epoxy. This resulted in higher compressive strengths than for uncapped specimens, but brooming failures still occurred. He then capped the ends of the specimens with tapered aluminum fittings (see Figure 39a). Much higher strengths were obtained, but failure usually occurred at the specimen-end cap junction. No end brooming was evident with this design, however. In order to promote failure within the gage section, he further improved his design by not fully tapering the end caps, and by waisting the gage section by machining. Ewin's final design is shown in Figure 39b. Failure did occur in the gage section of the specimen. Although this specimen required a significant amount of machining time and fabrication care, good reproducibility of results was obtained. In fact, it was this development with block compression specimens which very soon thereafter led Ewin and his colleagues [46,47] to develop the RAE Compression Test Method described in detail in the previous section. He considered the RAE specimen, a coupon of rectangular cross section, to be a two-dimensional analog of the cylindrical block specimen.

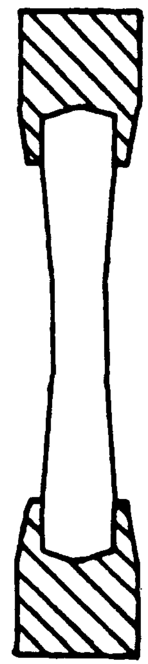
During this same late 1960's time period, Hadcock and Whiteside [58] also presented an alternative fixture configuration using a relatively thick specimen of rectangular cross section (see Figure 40). They also incorporated the two-dimensional analog concept of rotating end caps introduced by Texaco [55] with their cylindrical specimen, but the end caps were clamped onto the specimen rather than being adhesively bonded on. This makes specimen preparation, and specimen removal from the end caps after a test, much simpler.

Studies of block compression specimens have continued in this manner over the years. For example, Piggott and Harris [59,60] utilized cylindrical (pultruded) specimens of various unidirectional composites, including carbon, E-glass, and Kevlar fibers in a polyester matrix. The specimens were 0.24" (6 mm)" in diameter and were end-loaded by flat plattens after a steel collar was slipped over each end. Their fixture is shown in Figure 41. It will be noted that each collar contains a series of slightly different diameter holes. Thus, they were able to accommodate slight diametrical tolerance variations from specimen to specimen. It is interesting, however, that the tightness of fit of the specimens in the end fittings did not appear to influence the compressive strengths obtained [59]. Specimens fitting loosely and those forcibly pressed into the collars produced similar compressive strengths.

Such work has continued up to the present time. For example, Bethoney, et al. [61] used unidirectional composite specimens of both circular and square cross sections to test



a) First End-Capped Compression Specimen Configuration Developed



b) Final End-Capped Compression Specimen Configuration Developed

Figure 39. Short Block Compression Test Specimens Developed by Ewins [57]

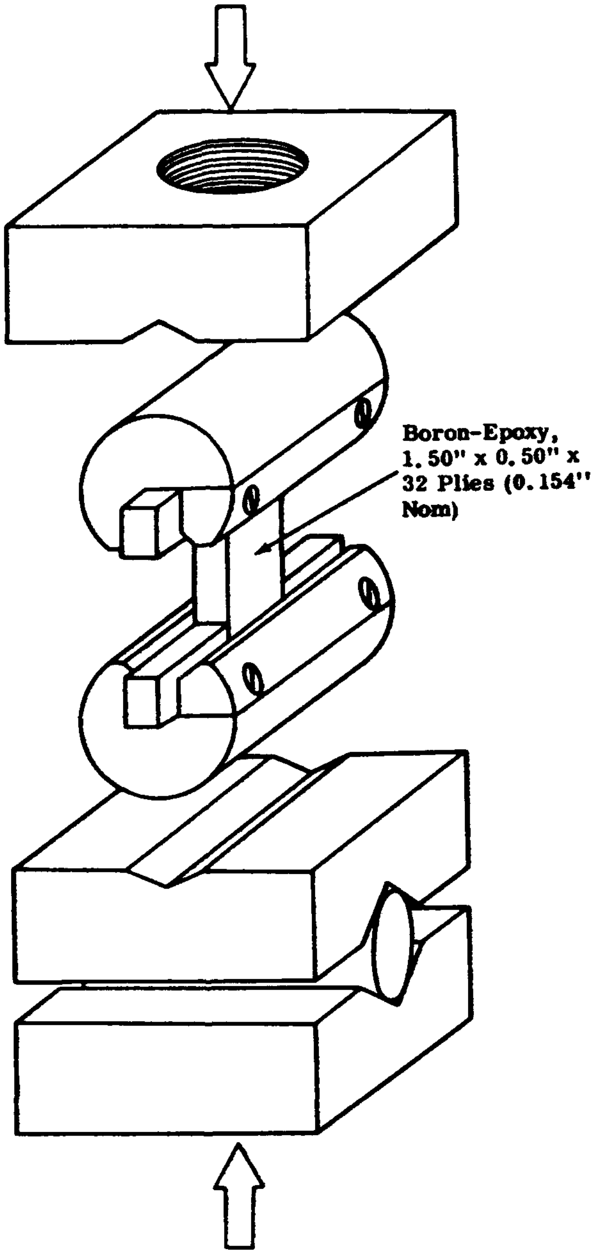


Figure 40. Schematic of Short Block Compression Test Specimen Configuration Used to Test Boron/Epoxy Composites [58]

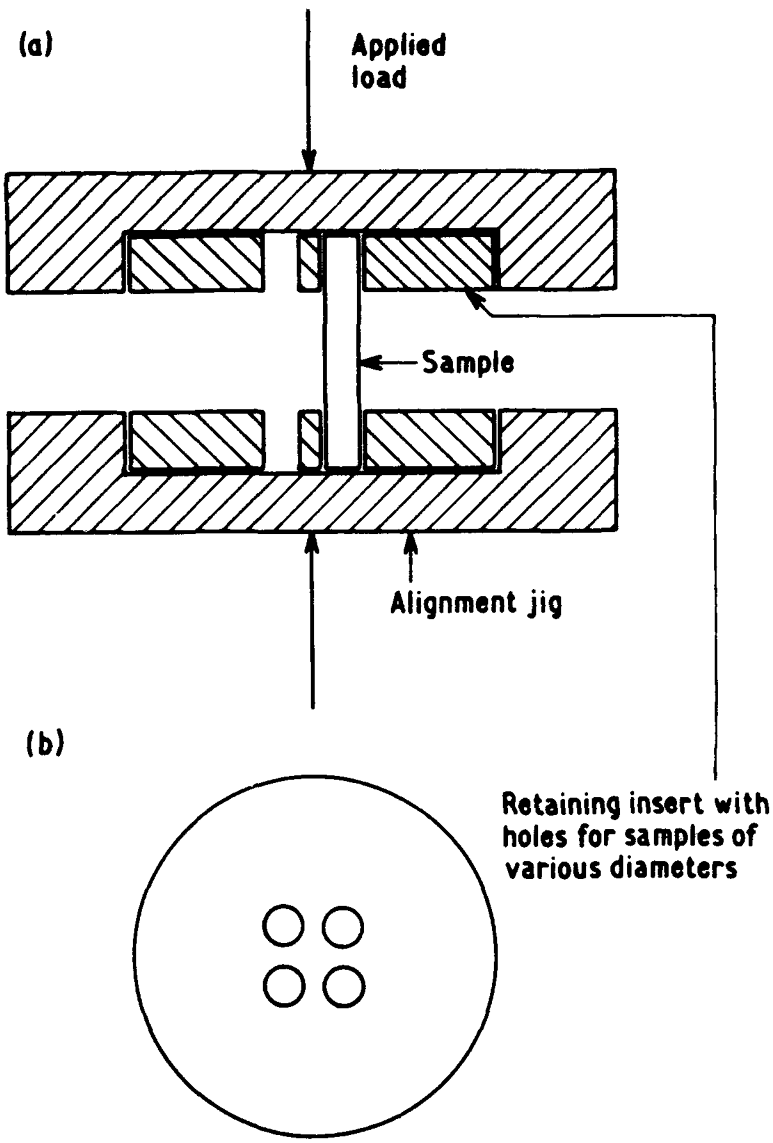


Figure 41. Compression Testing Arrangement: (a) Section Through Supports with Sample in Place, (b) View of the Upper Side of Lower Specimen Grip [60]

alumina fiber-reinforced magnesium metal-matrix composites. The cylindrical specimens ranged in diameter from 0.25" to 0.50"; the square specimens were 0.38" x 0.38" in cross section. The specimen length-to-diameter ratio in all cases was 2. Their test fixture, shown in Figure 42, was similar in principle to that used by Piggott and Harris [59,60], but with just a single hole in the collar. The circular specimens performed much better than the square specimens. However, even for the specimens of circular cross section, failures tended to initiate at the end of the collar, just as Ewins [57] had observed 20 years before. The square specimens failed by end brooming, presumably due to a poor fit of the collars at the specimen corners.

Stress States and Failure Modes

Stress concentrations are induced at the ends of any block specimen, which can lead to premature failures. This is true whether the specimen is reinforced (a composite) or not. Thus, flatness and parallelism of the specimen ends, and also of the loading platens, are critical, since the loading must be introduced very uniformly, to minimize end crushing. If end fittings are used their attachment, typically by adhesive bonding, induces another possible misalignment imperfection.

Only a simple σ = P/A stress calculation is necessary. Also, the specimen is typically long enough to permit strain gages or an extensometer to be used. However, it has frequently been reported that compressive strength results tend to be very scattered, particularly when testing high stiffness, high strength composites, because of the difficulty in controlling the perfection of the end conditions from one specimen to the next. Even Park, in his presentation of the Celanese Compression Test Method in 1971 [2], demonstrated this experimentally for the new high modulus carbon fibers being introduced by Celanese at the time.

Failures initiated at the specimen ends, or at the ends of end fittings if used, are unacceptable, and this is what frequently occurs. For this reason, block compression test methods are not commonly used at the present time for the compression testing of composite materials. However, when no end reinforcement is required and end crushing does not occur, which can be the case when testing relatively low strength composite materials, the block specimen represents the ultimate in specimen preparation and testing simplicity.

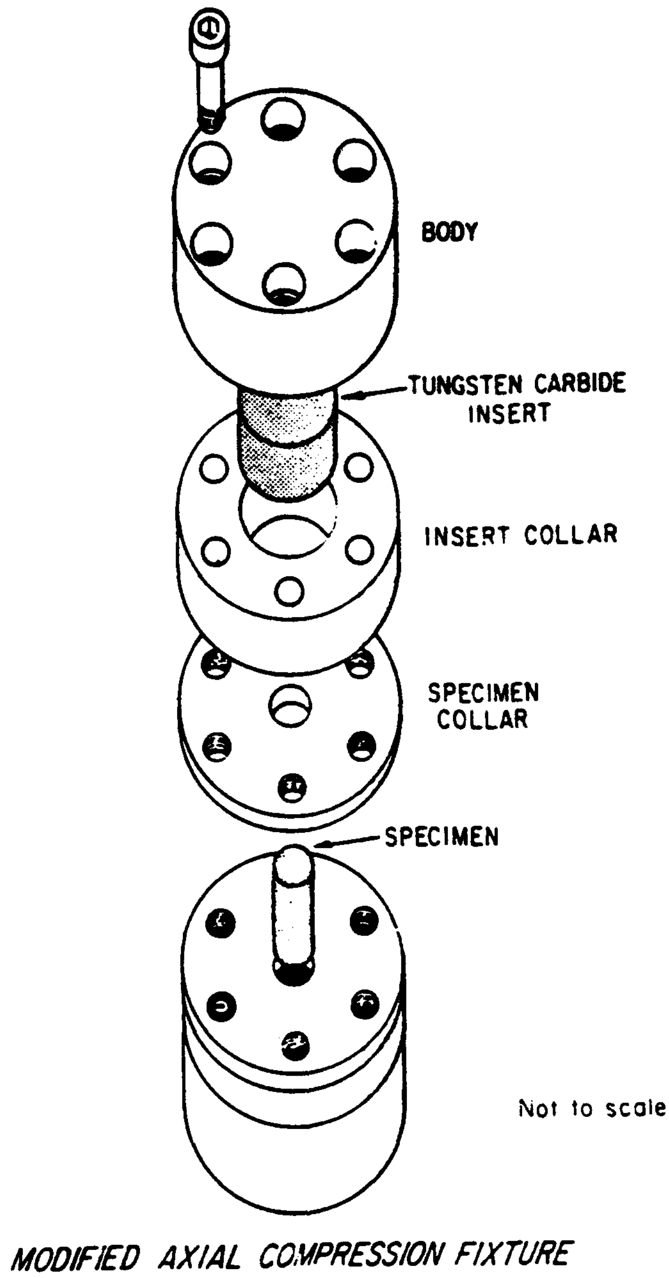


Figure 42. Short Block Compression Test Fixture [61]

Other Requirements and Modifications

Because of the simplicity of this test method, attempts to develop improved end constraint systems, for both circular and rectangular cross section specimens will undoubtedly continue, just as it has for the past more than 20 years. Also, there are always special testing situations where a simple block compression test method may be quite suitable. For example, in determining the transverse compression strength of a unidirectional composite, or the through-the-thickness compressive strength of a composite laminate.

3.3 SANDWICH-BEAM CONFIGURATIONS

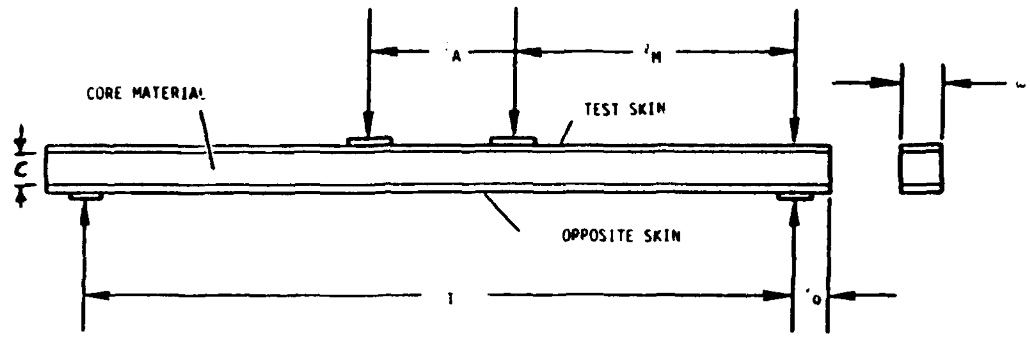
3.3.1 ASTM D 3410, Method C - Flexure, Compression Test Method

General Description of the Test Method

A sandwich beam is tested in four-point bending, as indicated in Figure 43 [1]. Typically the beam is fabricated of thin face sheets adhesively bonded to a honeycomb core. The ASTM Standard D 3410 [1] specifies a "heavy density core", but parenthetically indicates a 23 lb/ft^3, ⅛" hexagonal aluminum honeycomb core, using an adhesive such as FMS-3018 IB. Thus, it is quite specific in its recommendation. The compressive (upper) face sheet of the ASTM specimen is to be a 6-ply unidirectional composite. The tensile (lower) face sheet of the beam specimen is to be sufficiently strong so that it does not fail before the compressive face sheet since a compression test is being performed. The ASTM Standard recommends a tensile face sheet twice as thick. The specimen is 22" long and 1" wide, with the core being 1.5" thick. The support span is 20" and the loading span is 4".

As indicated in Figure 43, the ASTM Standard specifies that rubber load pads should be placed between the specimen and the fixture contact points, to prevent local damage to the face sheets. Two axial strain gages, bonded to the compressive face sheet 0.75" on opposite sides of the specimen midlength, are to be used if the axial compressive strain is to be monitored.

It should be noted that sandwich beams of this general configuration had been used by industry since at least the late 1950's, General Dynamics Corporation, Fort Worth, Texas



	Dimensions	
	mm	in.
ω	25.4	1.0
l_o	25.4	1.0
l_T	508.0	20.0
l_M	203.2	8.0
l_A	101.6	4.0
C	38.1	1.5

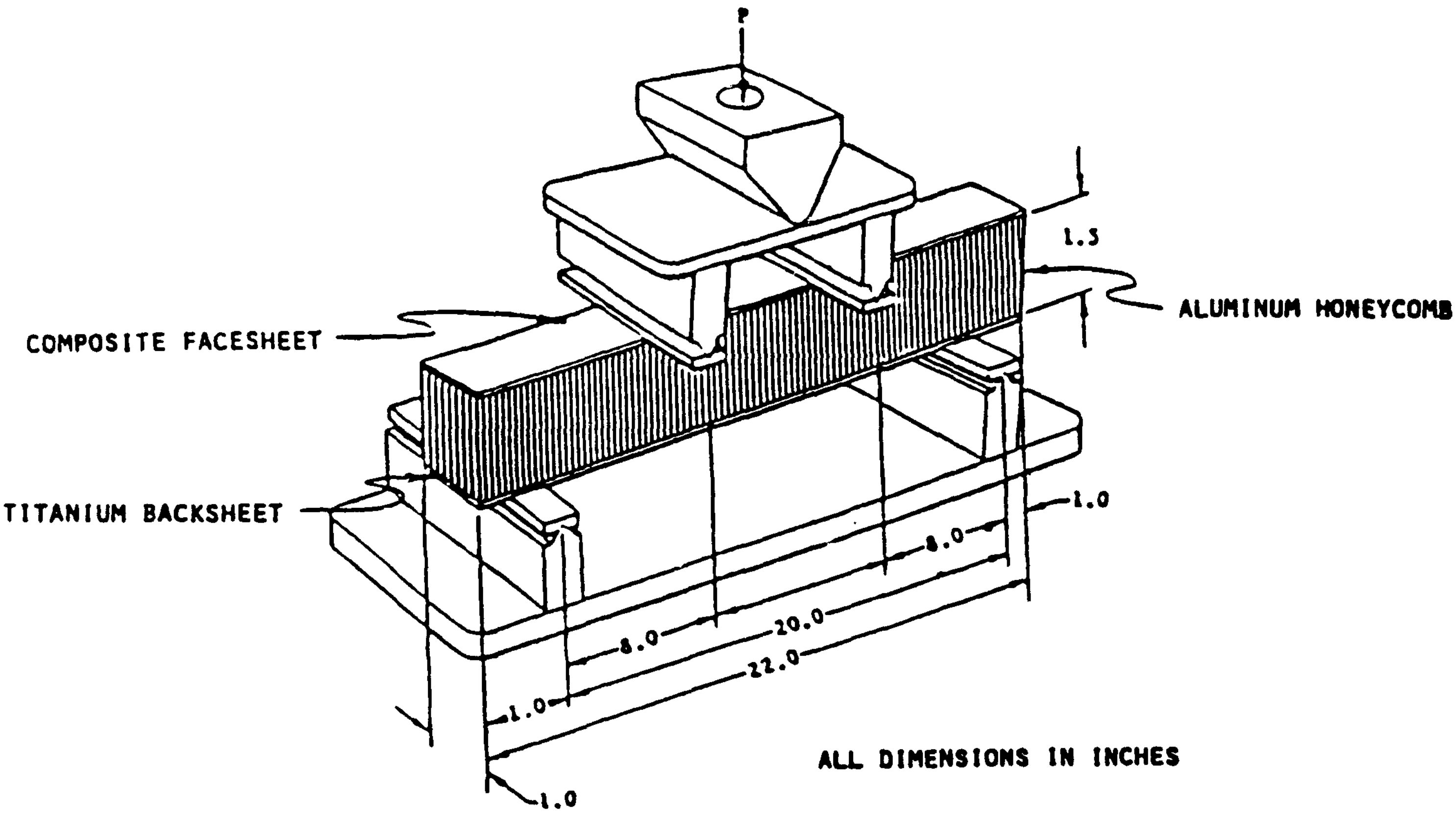


Figure 43. Sandwich Beam Compression Test Method [1]

Division, being a leading proponent of sandwich beam testing [62]. In fact, Hoffer and Rao [21] used almost exactly the same sandwich beam compression specimen as now specified in the ASTM Standard as a comparison method when introducing their IITRI Compression Test Method in 1977, ten years before the sandwich beam compression test method became an ASTM standard.

<u>Stress States and Failure Modes</u>

As specified in Section 10.1.2 of ASTM Standard D 3410 [1], the compressive strength of the composite being tested (the compressive face sheet of the sandwich beam) is calculated based upon classical beam theory. The assumption is that all of the bending stresses are carried in the thin face sheets. (The bending stresses in the core material are assumed to be negligible, a very good assumption because of the very low inplane stiffness of the honeycomb). Also, it is assumed that the axial compressive (and tensile) stresses in the face sheets are constant through their thickness. This is also a good assumption since the face sheets are very thin (the compressive face sheet, at 6-plies, being on the order of 0.030" thick) relative to the total beam thickness (which is on the order of 1.6" thick), i.e., the beam is over 50 times thicker than the compressive face sheet itself. Thus, the compressive strength can be calculated as

$$\sigma = P\, l_m / \{2wt_c\, [\, c + (t_c + t_t)/2\,]\}$$

where

- P = maximum force applied by testing machine
- l_m = length of moment arm (see Figure 43a)
- w = width of composite face sheet
- t_c = thickness of composite compressive face sheet
- t_t = thickness of composite tensile face sheet
- c = thickness of core

The compressive modulus is calculated from the slope of the initial, straight line portion of the stress-strain curve in the usual manner. If the ASTM-recommended two strain gages

are used, the Standard states that the readings should not differ by more than 10 percent, and that differences less than 5 percent are attainable. It is presumed that, if the two gage readings are within this acceptable difference, they can be averaged to obtain the strain in the face sheet, although the Standard does not so state.

The compressive face sheet is supposed to fail first if a valid test is conducted. However, this may not always happen. For example, Shuart [63] tested HTS1/PMR-15 carbon fiber-reinforced polyimide composites with $[0]_8$ face sheets, six specimens at room temperature and three each at temperatures of -157°C (-250°F) and 316°C (600°F). None of the 12 specimens failed in a valid failure mode. They all failed either due to core crushing at one of the loading points, or due to debonding of the compression face sheet from the core. It should be noted that he also tested specimens with $[90]_8$, $[\pm 45]_2$, and $[0/\pm 45/90]_s$ face sheets, with almost equally poor results. Only half of the room temperature specimens of each of these lay-ups, and none of the specimens tested at either of the other two temperatures, failed in an acceptable mode. While this is an extreme case, it does indicate the problems involved in fabricating acceptable sandwich beam flexural compression test specimens, and is not an isolated case.

Using a finite element analysis scheme, Shuart [63] studied the effect of the honeycomb core on measured composite compressive properties. He used aluminum as well as titanium alloy honeycomb as the sandwich cores. He concluded that essentially all the compressive load was carried by the upper composite face sheet and that nearly uniaxial compressive stress state existed in the upper face sheet. Therefore, the bending stresses in the core was found to be negligible, as assumed by other researchers. However, the type of honeycomb core material was found to have influenced the type of failure of the sandwich beam.

Other Requirements and Modifications

As suggested above, the principal difficulty of the Sandwich Beam Flexure Compression Test Method is in making an acceptable sandwich beam. For investigators familiar with this specialized construction this is not a major problem. However, for others it typically is. There are many critical parameters that affect the results, such as type and thickness of face sheet material being tested, adhesive used, core used, and fabrication technique used. In addition, the fabrication of a sandwich beam specimen is relatively expensive, and a considerable

amount of the test material is consumed in each specimen. For all of the above reasons, this test method is not commonly used, even though it is now part of ASTM Standard D 3410.

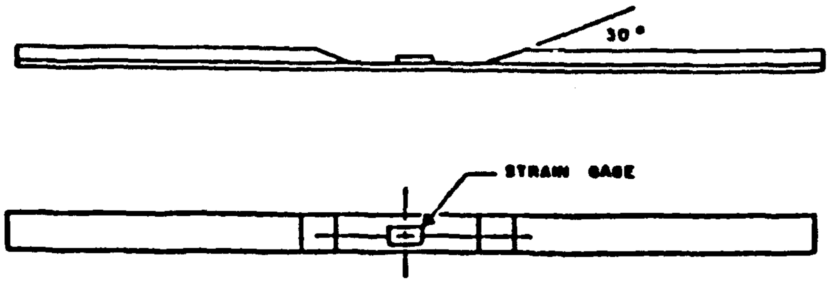
It should be noted that there have been attempts to circumvent some if not all of the above difficulties. One such study was that by Gruber, et al. [64]. They developed a reusable sandwich beam concept, as shown in Figure 44. As can be seen, the core and lower (tensile) face sheet are fabricated as a unit and are reusable. The compressive face sheet to be tested is prepared in the form of a tabbed, straight-sided specimen, but with tabs on only one face. This special specimen is clamped to the reusable portion of the beam at each tab end. The specimen is not bonded to the reusable portion. Thus, it can buckle upward when the compressive loading is applied via flexure even though it is restrained from displacing (buckling) downward. Although not mentioned at all in their paper, the specimen curvature induced when the bending load is applied does aid in resisting buckling, but it does not necessarily prevent it. This appears to be an important point.

The authors did not report encountering a buckling problem with the specimens they tested. However, this may have been because their specimens (E-glass, Kevlar 49 or intermingled E-glass and Kevlar fibers in a phenolic matrix) were relatively thick (24 plies), and *more importantly, failed at very low compressive* strength levels. Even the unidirectional E-glass/phenolic composites were indicated to have failed at very low compressive stresses. Although there appears to be some confusion with the numerical results presented in the paper [64], a compressive strength of only about 4.5 ksi is indicated for the reusable beam test, and only about 28 ksi for a comparison IITRI test of the same material. For the all-Kevlar 49 fiber composite and all of the hybrids, the strengths for both the reusable sandwich beam test and the comparison IITRI test were all even lower than 4.5 ksi. Thus, the authors did not give the new concept a very rigorous trial. With the 2" unsupported gage length indicated in Figure 44, specimens of higher strength would almost certainly have buckled.

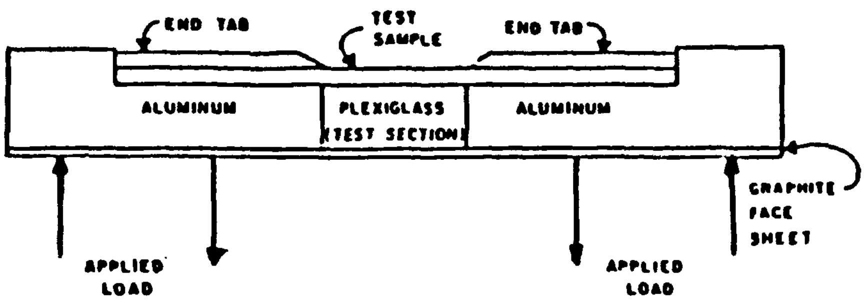
3.3.2 Sandwich Column Axial Loading Compression Test Method

General Description of the Test Method

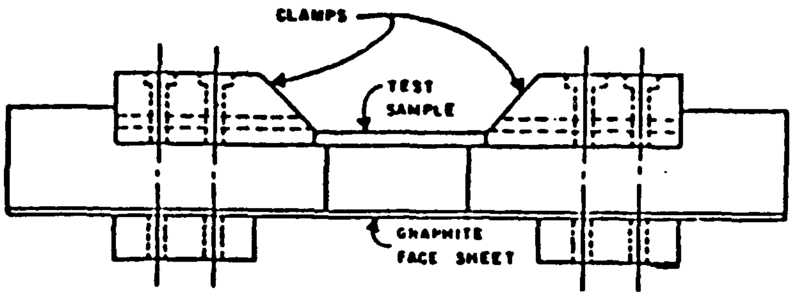
The sandwich column specimen consists of thin composite face sheets bonded to a core material, typically honeycomb, but possibly a low density polymer foam instead. This



a.) Test Specimen



b.) Reusable Sandwich Beam Compressive Test Fixture and Specimen (Without Clamps in Place)



c.) Complete Assembly

Figure 44. Reusable Sandwich Beam Compression Test Fixture [64]

sandwich panel is loaded in direct axial compression in its plane rather than in bending as for the test method described in the previous section. Thus, the sandwich column must be sufficiently short relative to its thickness to preclude buckling, and adequate end fittings must be used to prevent end crushing.

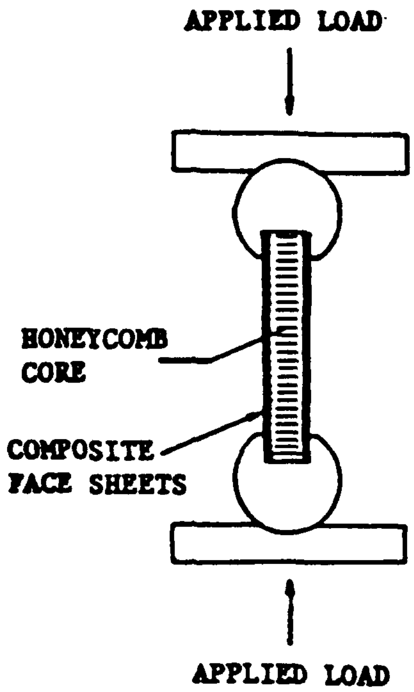
One version of this test method is defined by ASTM Standard C 364 [65], which was first introduced in 1955. In fact, although reapproved as recently as 1988, it has not been revised since 1961. That is, unlike many of the other composite material testing standards, it has been in existence for a long time. Figure 45a shows the general ASTM test specimen and loading apparatus configuration. Difficulties encountered in loading the two faces evenly, and preventing brooming of the face sheets at the load points are typical problems.

The ASTM Standard specimen is to be at least 2" wide, but not less than twice the total thickness of the sandwich laminate. For very large core cells, additional restrictions apply. The unsupported length of the specimen (length between end fittings) is to be not greater than twelve times the total thickness of the sandwich laminate.

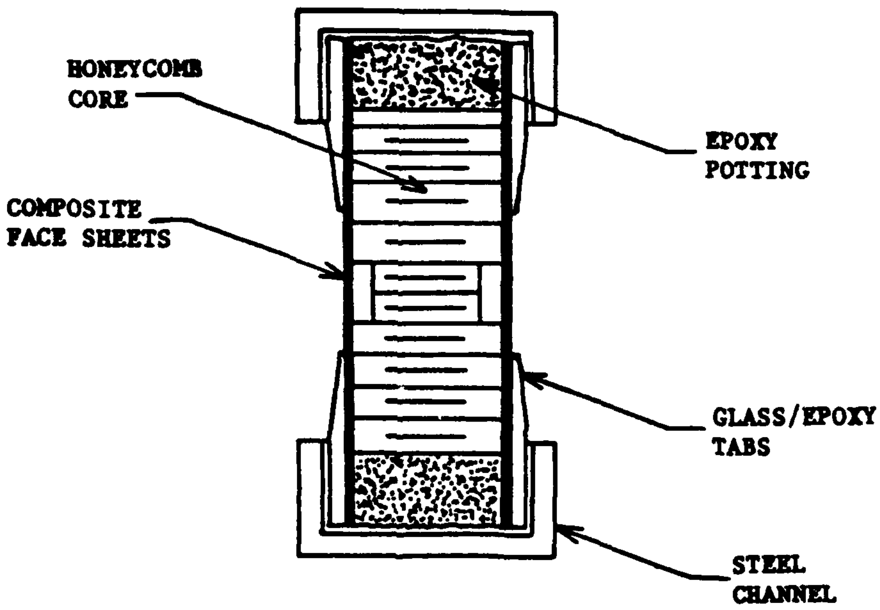
As indicated in Figure 45a, each end of the sandwich specimen can be snugly fit into a slot in a circular cylinder. This is the most common end fitting used. As an alternative, the ASTM Standard C 364 [65] permits the use of end clamps made of rectangular steel bars lightly clamped to the specimen. Casting of the ends of the sandwich specimen in a polymer or even plaster of Paris is also mentioned. These alternatives to the circular cylinder end fittings have not found great success with other than very low strength face sheet sandwich structures, however.

Stress States and Failure Modes

Just as for all end-loaded compression specimens, stress concentrations exist at the specimen ends. If end fittings are used, as in the present case, then stress concentrations at the junction of the end fittings and the sandwich laminate specimen may induce premature failures in the face sheets at these points. Thus, it is critical that a valid failure mode be obtained, i.e., a failure in one or both of the face sheets away from the specimen end fittings, in the absence of gross or local face sheet buckling, or face sheet debonding from the core material.



a) ASTM C 364 Edgewise Compression Test Fixture and Specimen [65]



b) Convair Edgewise Compression Sandwich Test Specimen [25]

Figure 45. Sandwich Column Compression Test Specimen Configurations

To quote ASTM Standard C 364, "The sandwich column, no matter how short, usually is subject to a buckling type of failure unless the facings are so short that they themselves are in the short column class. The failure of the facings manifests itself by wrinkling of the facing, in which case the core deforms to the wavy shape of the facings; by dimpling of the facings into the cells of honeycomb or gridded type cores; or by bending of the sandwich, resulting in crimping near the ends due to shear failure of the core or perhaps failure in the facing-to-core bond" [65].

Assuming a valid failure mode is obtained, the compressive strength is calculated as the applied force at failure divided by the total cross-sectional area of the two face sheets. (It is assumed that the core material carries negligible load, a very reasonable assumption for most core materials.) ASTM Standard C 364 suggests measuring the axial strain in each face sheet. The loading is sufficiently uniform if the difference in strain readings from one face sheet to the other is less than 5 percent. Compressive modulus is then determined in the usual manner, i.e., as the initial slope of the resulting axial compressive stress - axial compressive strain curve.

Other Requirements and Modifications

Hertz, et al. [66] performed their own investigation of sandwich column compressive properties in the early 1970's. Driven primarily by disenchantment with coupon specimens and the lack of an industry-accepted compression test specimen, they developed a special sandwich column compressive specimen specifically for high modulus fiber composites. Work progressed from the basic ASTM Standard C 364 specimen configuration [65] to a final version utilizing glass/epoxy end tabs bonded into a steel channel to provide additional end support. Data obtained with this specimen were substantially higher than those they obtained with the Northrop compression test fixture [66], and resulted in less scatter than for the specimen without the channel supports. Figure 45b illustrates the final specimen design they developed. It is somewhat complex, and not used today.

More recently, Lagace and Vizzini [67] also studied the sandwich column test method. There specimen is illustrated in Figure 46. A lightweight aluminum honeycomb was used in the central region, and a denser aluminum honeycomb at the ends. Glass/epoxy tabs were then bonded to the specimen ends. The specimen was gripped in the standard hydraulic grips

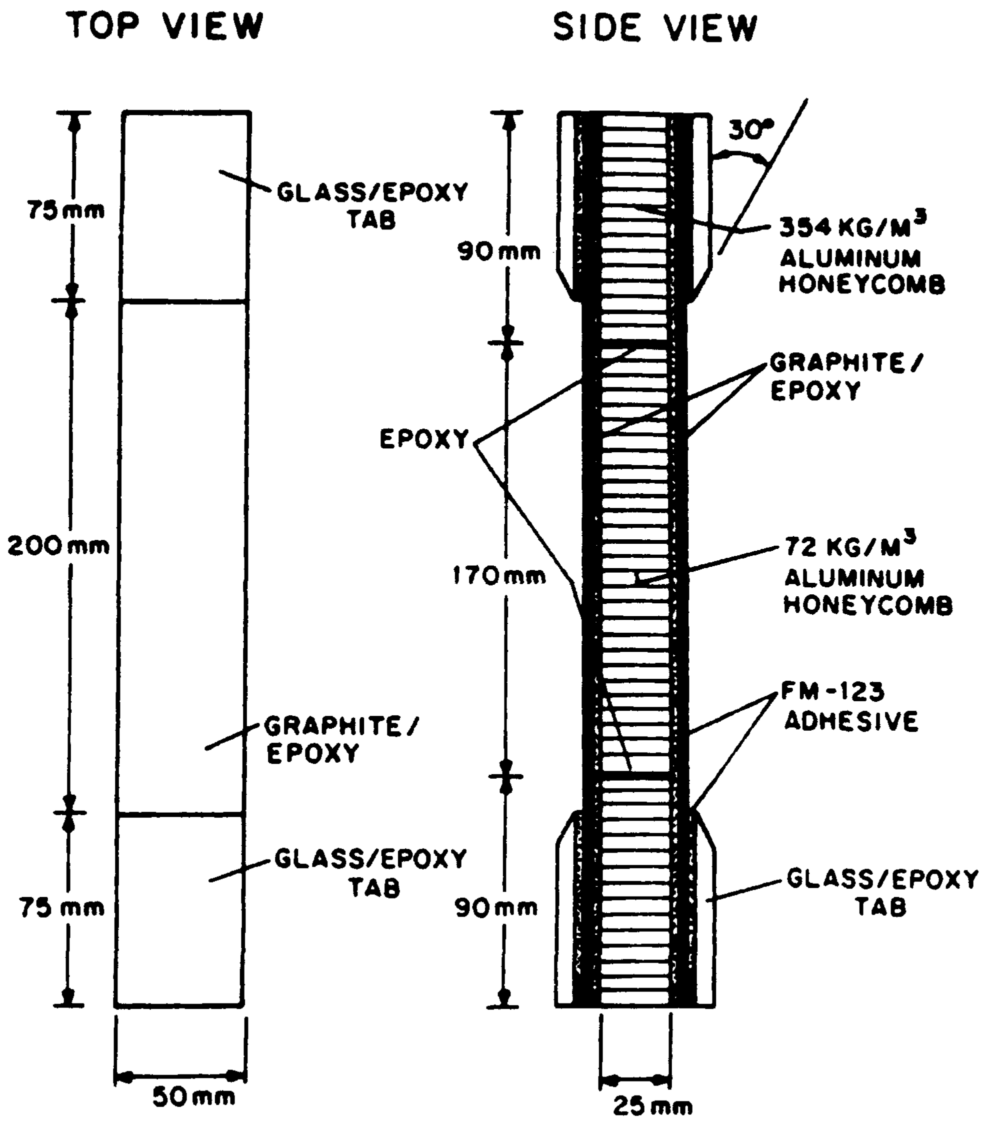


Figure 46. Schematic of the Sandwich Column Compression Test Specimen as Developed by Lagace and Vizzini [67]

of a testing machine and loaded in compression. The dense core in the end regions and the presence of the tabs on the outside permitted adequate gripping forces to test the various angle-ply laminates. However, solid aluminum core had to be substituted for the honeycomb when testing the unidirectional composites.

It will be noted that the specimens were 13.8" (350 mm) long and the ASTM-required 2" (50 mm) wide. The unsupported length was only on the order of six times the specimen thickness, well within the ASTM-required [65] maximum of twelve times the specimen thickness.

The demonstration test program conducted by Lagace and Vizzini [67] included 140 column specimens, incorporating either six, ten, or twelve-ply carbon/epoxy facesheets. Most of the specimens (95) incorporated Hercules AS1/3501-6 carbon/epoxy facesheets, the remaining 45 being the newer AS4/3501-6 composite. In addition to unidirectional composites, various angle-ply face sheets were also tested. Typically, five replicate tests were performed for each test configuration. For the unidirectional composites, a compressive strength of about 175 ksi was obtained for the twelve-ply AS1/3501-6 composite, and about 205 ksi for the ten-ply AS4/3501-6 composite.

These values are reasonably comparable with corresponding values obtained from both shear-loaded and end-loaded tests of solid laminates of the same type of material (see, for example, References [4,7,10-12,25,26,36]). They are not higher values. The failure modes appeared to be valid. The obvious advantage of such a test method therefore remains not in being able to obtain higher compressive strengths, but rather in being able to test very thin composites, just as was the case for the sandwich beam flexure compression test method described previously. Correspondingly, the disadvantage is also the same, viz., the higher cost of preparing the test specimens.

3.3.3 Mini-Sandwich Column Axial Loading Compression Test Method

General Description of the Test Method

This is a recently introduced variation of the Sandwich Column Axial Loading Compression Test Method discussed in the previous section, developed by Crasto and Kim [68] at the University of Dayton Research Institute. It is also discussed in Reference [69].

Rather than using a sandwich laminate with a honeycomb or foam core, the core is a solid, unreinforced polymer, usually of the same material as the matrix used in the composite to be compression tested. The specimens were 5" long and 0.25" wide. The unreinforced polymer core was 0.125" thick, and the face sheets were either 2, 4, or 6 plies thick. In the limited work performed to date [1], glass/epoxy tabs were bonded to the sandwich to form a specimen with an untabbed (gage) length of 0.50" that was tested in a standard IITRI test fixture. Results indicated fewer problems with failures in the tab regions than when testing solid laminates such as a standard IITRI compression test specimen, although some tab failures did still occur.

What justifies including this new approach here as a separately discussed compression test method, however, are the very high compressive strengths obtained by Crasto and Kim [68]. They tested S-glass/1034 epoxy (ICI-Fiberite), AS4 carbon/3501-6 epoxy (Hercules), and AS4 carbon/APC-2 PEEK (ICI-Fiberite). The corresponding average compressive strengths were 330 ksi, 293 ksi, and 228 ksi, respectively. These strengths are each about 75 ksi higher than typically obtained using any of the other test methods discussed here. In fact, Crasto and Kim [68] did test the same materials using a standard (solid laminate) IITRI compression test specimen. They obtained strengths of 203 ksi, 186 ksi, and 160 ksi, respectively for the three materials. While these are slightly lower than most current literature values (see, for example, References [7,10,11,36,70), they are not unreasonable.

Crasto and Kim [68] also performed four-point flexure tests on their solid core mini-sandwich specimens. The failure modes were typically not acceptable, however. Premature core fracturing, and delamination of the face sheets from the core, frequently occurred. Thus, although higher strengths were obtained than for the standard IITRI specimens, the results were erratic, being a function of the specific failure mode that occurred.

Stress States and Failure Modes

The compressive stress in the mini-sandwich specimen was calculated using a simple rule-of-mixtures relation, assuming the core material carries load in direct proportion to its stiffness relative to the stiffness of the face sheets. Thus, the composite face sheet compressive strength σ_f is calculated as [68]

$$\sigma_f = (\sigma_t - \epsilon_t E_c V_c) / V_f$$

where

σ_t = compressive strength of entire sandwich, i.e., P/A, where P is the total force on the sandwich specimen at failure and A is the total cross-sectional area of the sandwich specimen

ϵ_t = axial strain at failure of the sandwich specimen

E_c = axial modulus of the core material

V_c = volume fraction of core material

V_f = volume fraction of face sheet material, i.e., $V_c + V_f = 1$

Although no analysis of the mini-sandwich specimen loaded in axial compression has been performed to date, it is possible that the resin core softens the test specimen at the grip/tab ends sufficiently to reduce the induced stress concentrations there. The core material also is obviously very effective in supporting the thin composite material face sheets against buckling. In fact, the 6-ply composite face sheet mini-sandwich specimens were not satisfactory in that they did buckle before failing in compression, even though the buckling stresses themselves were impressively high, e.g., about 250 ksi for the AS4/3501-6 carbon/epoxy composite. Thus, the authors recommended using either 2- or 4-ply face sheets.

Certainly the volume of composite material exposed to the compressive stress is less than in solid laminate specimens, making the presence of material imperfections statistically less. How important this factor is remains as an unknown.

The failure modes observed by Crasto and Kim [68] suggests that actual compression of individual fibers occurred in many cases. Whether this failure mode can be achieved in a solid laminate in a structure has not yet been established. That is, the mini-sandwich test method may be forcing a (desirable) failure mode that unfortunately cannot be achieved in an actual composite structure.

Other Requirements and Modifications

Although a sandwich laminate rather than a solid laminate must be prepared, the fact that the core is unreinforced resin, cocured with the composite face sheets, makes fabrication

relatively straightforward. Also, standard compression test fixtures can be used, which is an advantage.

Not enough testing has been performed to date to make a determination as to the consistency of results obtained. Preliminary data indicate the attainment of compressive strengths significantly higher (viz., in the range of 25% higher) than those obtained using solid laminates. It will be interesting to determine if other investigators can duplicate these very high strength values in a repeatable manner.

4. DETAILED REVIEW OF ANALYTICAL STUDIES

This review of existing analytical studies is intended to supplement the discussion of the various individual test methods presented in the previous sections. As will be noted in the following, the extent of detailed studies reported in the literature is still very limited. Much more work remains to be done. As described in the INTRODUCTION, there are two basic compression specimen loading methods, viz., shear loading through the lateral surfaces of the test specimen and direct end loading. In the following, the shear loading technique will be analyzed first. As discussed in the previous sections, and as will be indicated below, although there are a number of different test methods within each of these two basic loading method classes, the analyses are similar for all test methods within each of the classes. Thus, each specific test method need not be discussed in detail. One of the more commonly used methods will be presented in detail, and then only the differences noted for the various other methods of that class.

4.1 IITRI SPECIMEN

Several two-dimensional linear elastic finite element analyses have been performed to study the stress states and failure modes of IITRI specimens [12,13,71,72]. Typical finite element grids of the specimen are shown in Figure 47 [12]. Existing formulations are based on either the assumption of plane stress or plane strain, and uniform displacement and stress boundary conditions have both been applied [71].

The predicted effects of type of tab material used are presented in References [71,12]. Figure 48 presents predicted stress distributions in the specimen for three types of tab material and two types of layups for the tab material. Three types of tab material were considered, viz., steel, an AS4/3502 graphite/epoxy composite, and an E-glass/epoxy composite. The peak stress in the specimen was considerably lower when the E-glass/epoxy composite was used for the end tabs rather than either of the other two material systems [71].

High stress concentrations at the tab tip may trigger failure, although it can be reduced by reducing the tab taper angle. Figure 49 presents the peak stresses at the tab tips for both 90° and 10° taper angles, for the three different tab materials, respectively [12].

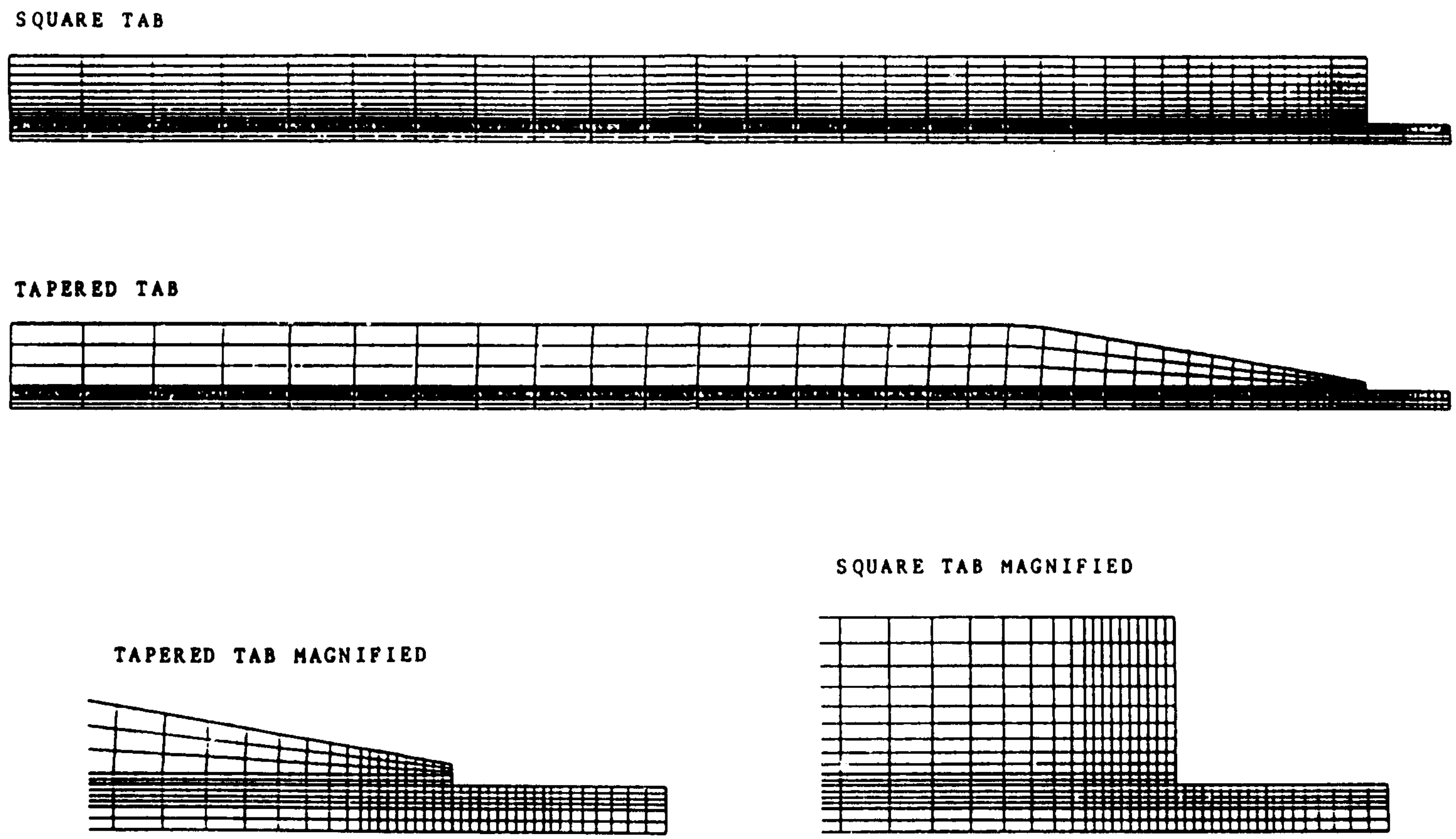
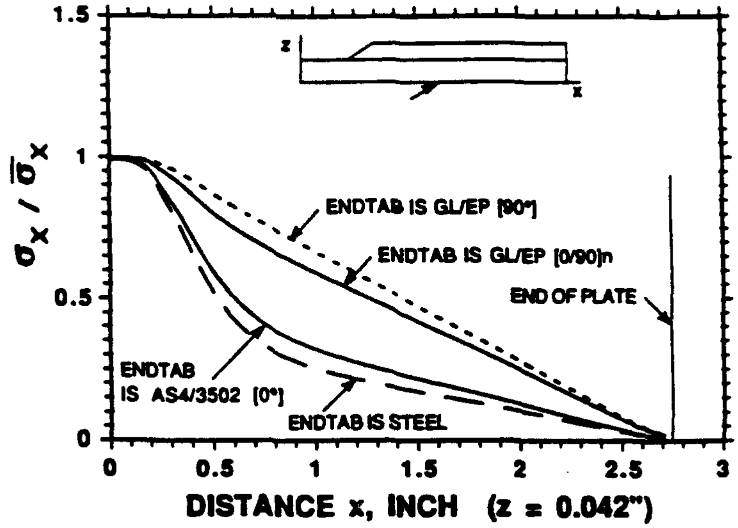


Figure 47. Typical Finite Element Grids Used to Model IITRI Compression Test Specimens [12]



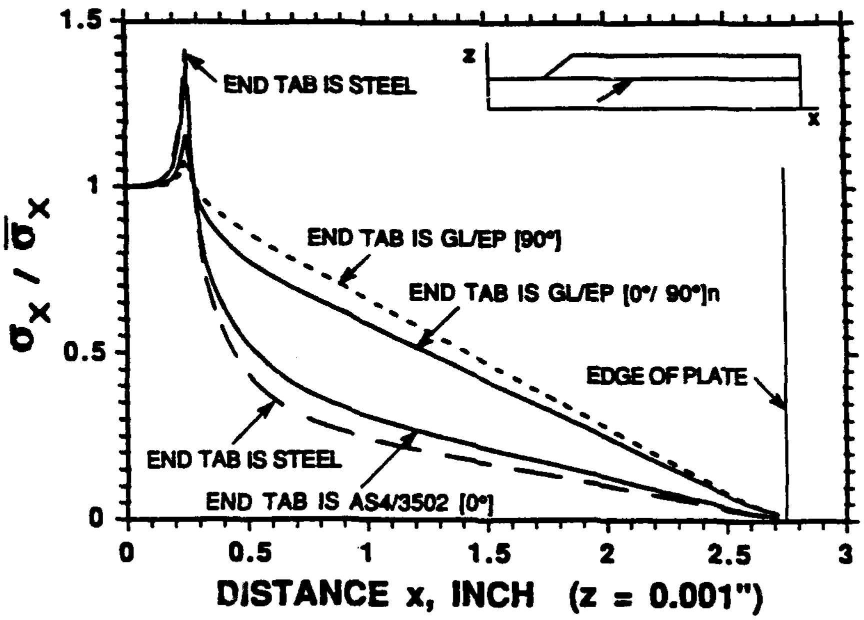


Figure 48. Stress Distributions in an AS4/3502 Carbon/Epoxy Unidirectional Composite IITRI Specimen for Three Tab Materials [71]

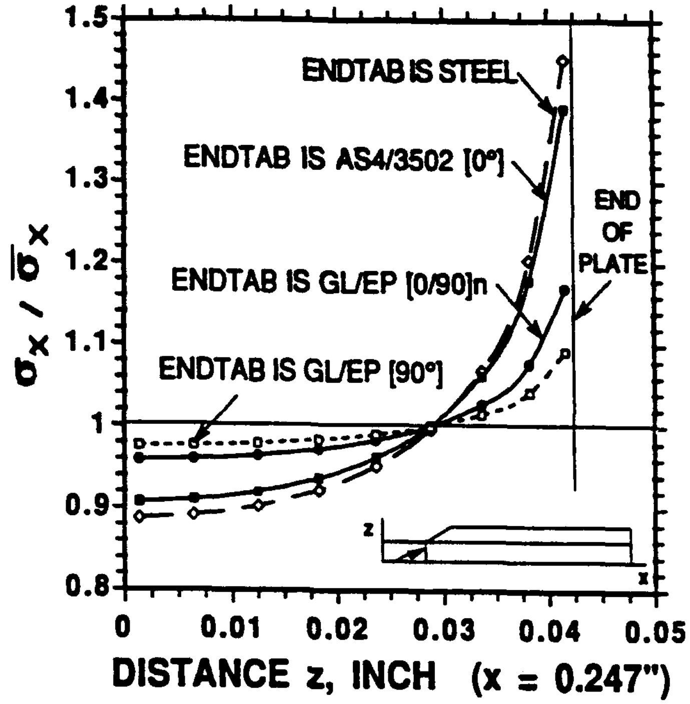


Figure 48. Stress Distributions in an AS4/3502 Carbon/Epoxy Unidirectional Composite IITRI Specimen for Three Tab Materials [71] (Cont'd.)

There was no noticeable difference in the predictions of the stress distributions in the specimen whether the adhesive layer was taken into account or not (Figure 50). The thicknesses of the adhesive layer was assumed to be 0.005" (0.127 mm), 0.003" (0.076 mm), or zero (no adhesive layer), respectively, in the analysis model [71].

The predicted stress states in four critical areas of the specimen are illustrated in Figures 51 through 55. Four different thicknesses were considered, viz., 0.50" (12.7 mm),).34" (8.64 mm), 0.175" (4.45 mm) and).085" (2.16 mm). The results are presented for stress and displacement boundary conditions, respectively [71]. The stress distributions were predicted in all cases except for the thinnest specimen to be nonuniform throughout the thickness in the gage section [71]. The tab tip stresses increased with increasing thickness, which is also evident in Figure 56, for the three thicknesses considered, viz., 0.125" (3.17 mm), 0.104" (2.64 mm) and 0.062" (1.58 mm) [12].

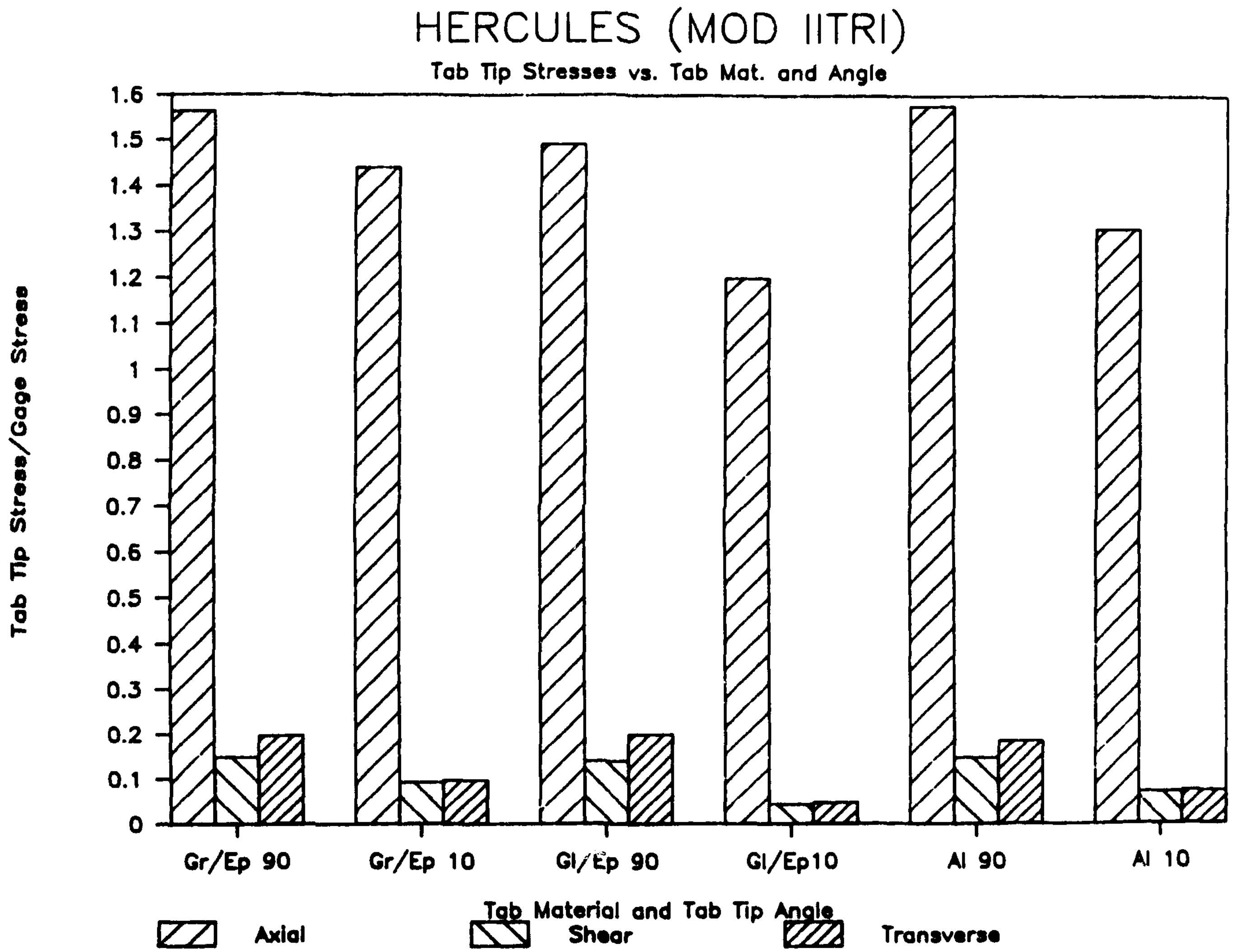


Figure 49. Peak Stresses at the Tab Tips for Various Taper Angles and Tab Materials [12]

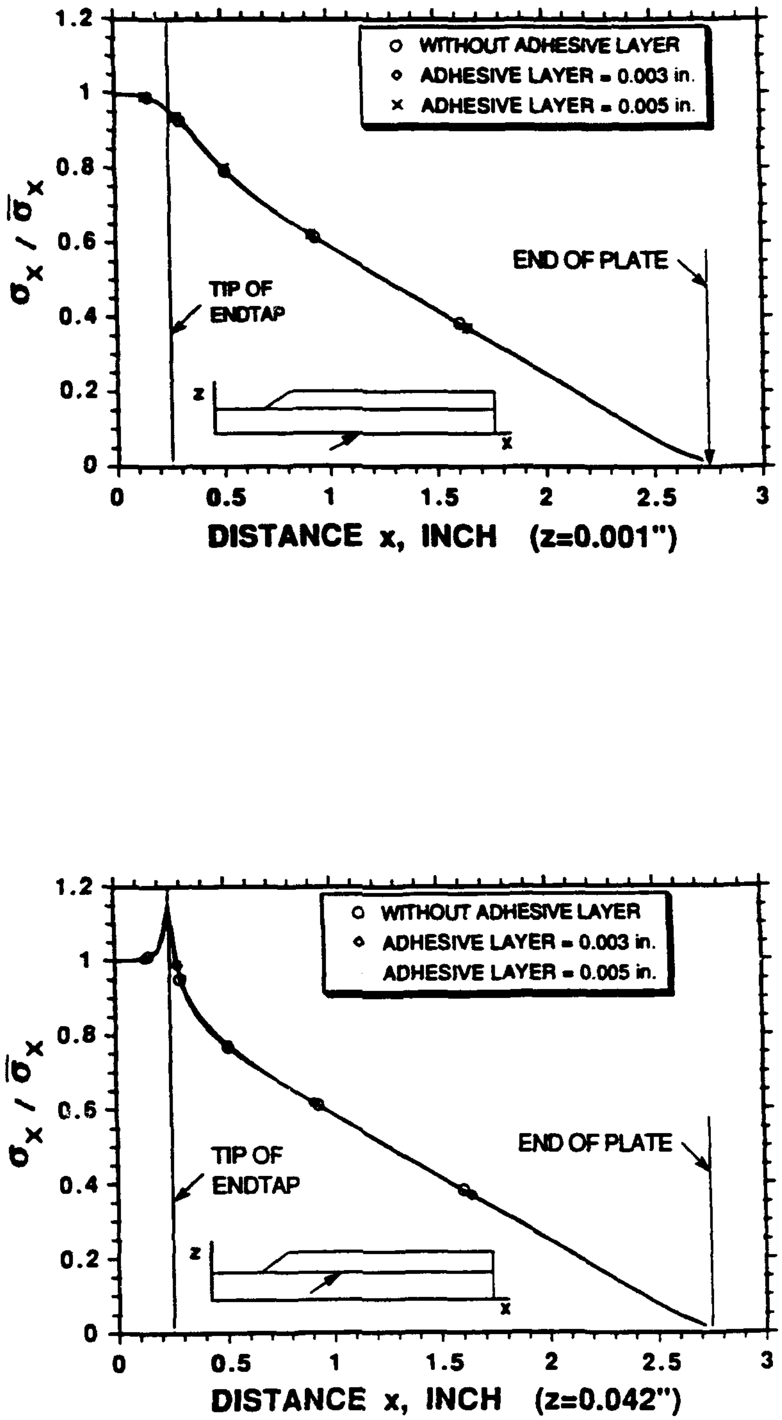


Figure 50. Stress Distributions in an AS4/3502 Carbon/Epoxy Unidirectional Composite IITRI Specimen for Three Adhesive Layer Thicknesses [71]

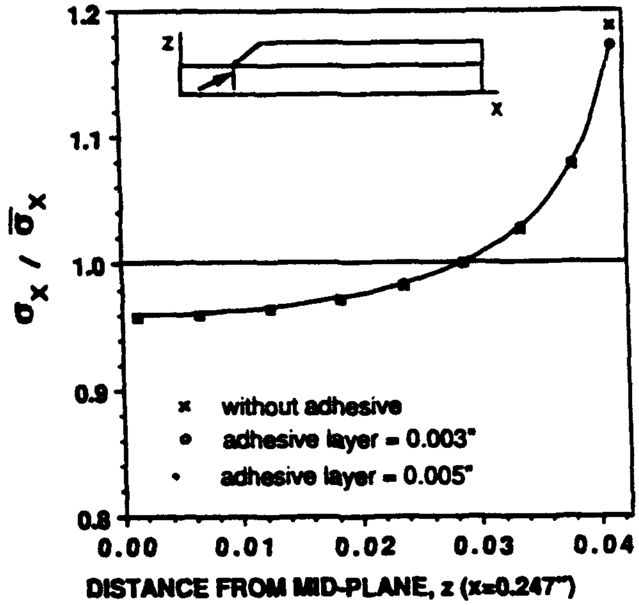
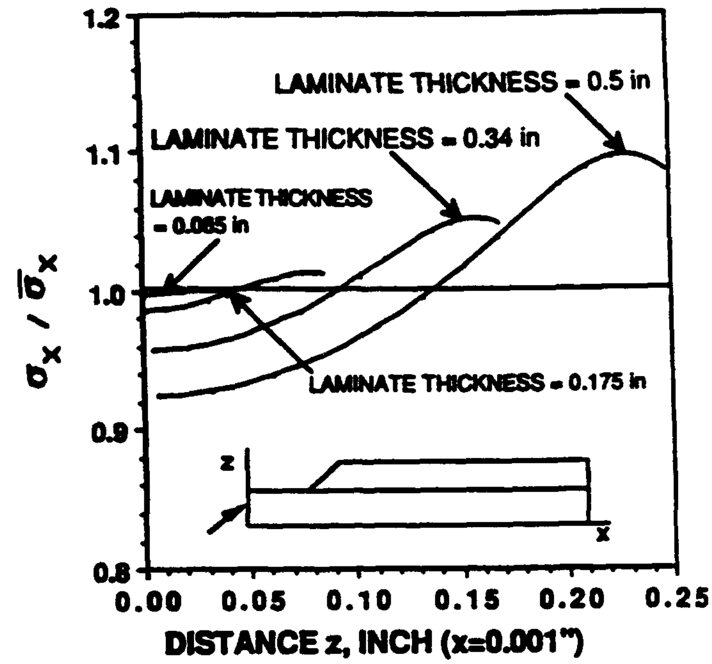


Figure 50. Stress Distributions in an AS4/3502 Carbon/Epoxy Unidirectional Composite IITRI Specimen for Three Adhesive Layer Thicknesses [71] (Cont'd.)

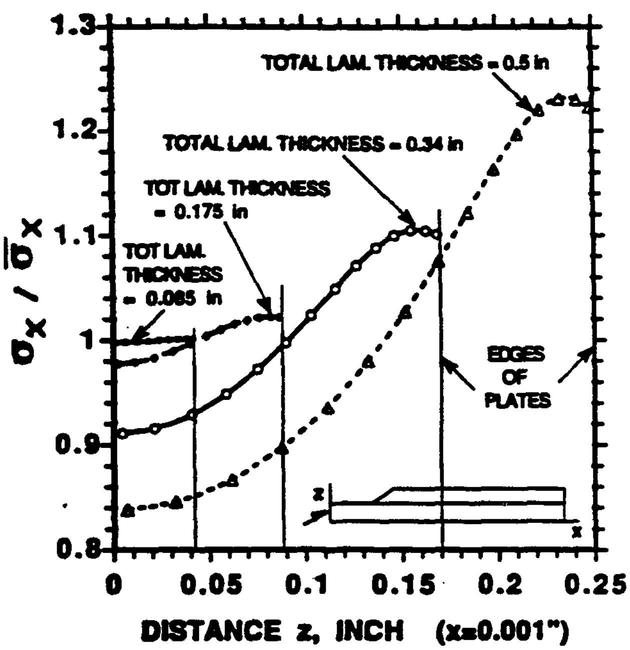
The gage length had no noticeable effect on the stress states in the specimen for a given material system, since instability was not analyzed. Even when the gage length was shortened to 0.10" (2.54 mm), no change was noticed in peak stresses at the tab tip [12].

However, the stress state does depend on gage length for various degrees of material orthotropy. A methodology for selecting specimen geometries as a function of material orthotropy and laminate thickness is presented in Reference [13].

Various orthotropy ratios (ratio of axial to shear modulus) of composite materials, varying from 20 to 325, were considered. A two-dimensional linear elastic finite element analysis and an elasticity solution based on Saint-Venant's principle for an upper bound estimate on stress decay length was utilized in a parametric study involving combinations of specimen geometries with varying material anisotropy. The steel wedge grip was also included in the analysis model. Based on the degree of material orthotropy and anticipated failure strain, the appropriateness of the test method for a given material system was evaluated (Figure 57).

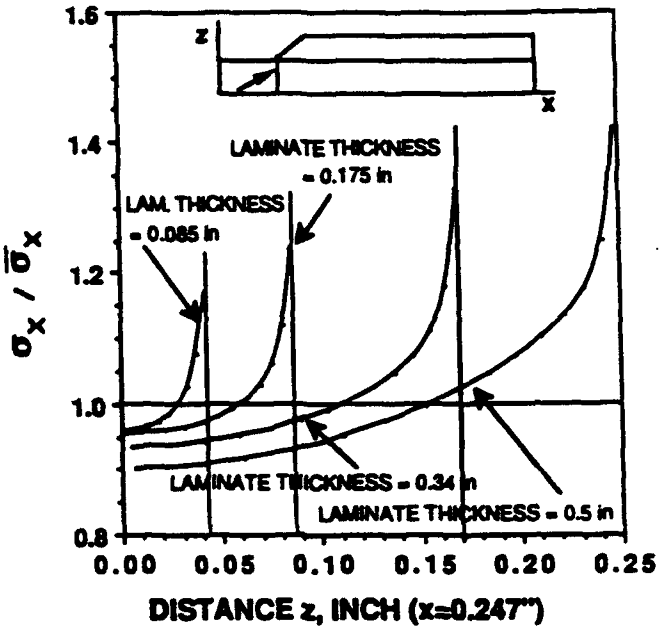


a. Applied uniform stress boundary conditions.

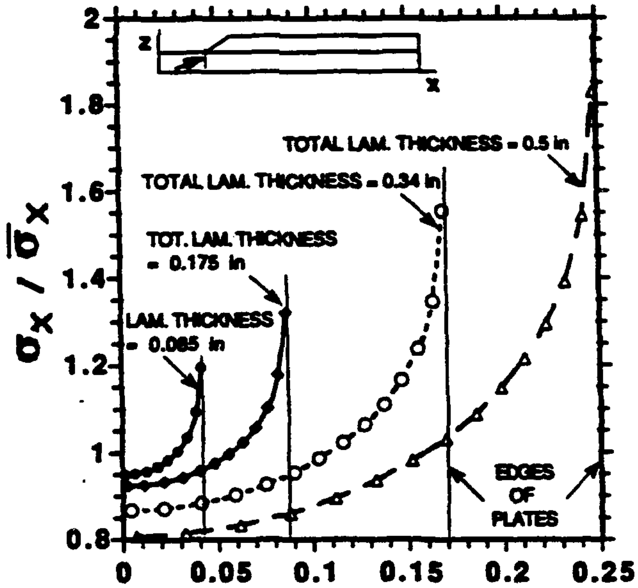


b. Applied uniform displacement.

Figure 51. Axial Stress Distributions in an AS4/3502 Carbon/Epoxy Unidirectional Composite IITRI Specimen, Through the Thickness in the Middle of the Gage Section, for Four Laminate Thicknesses [71]

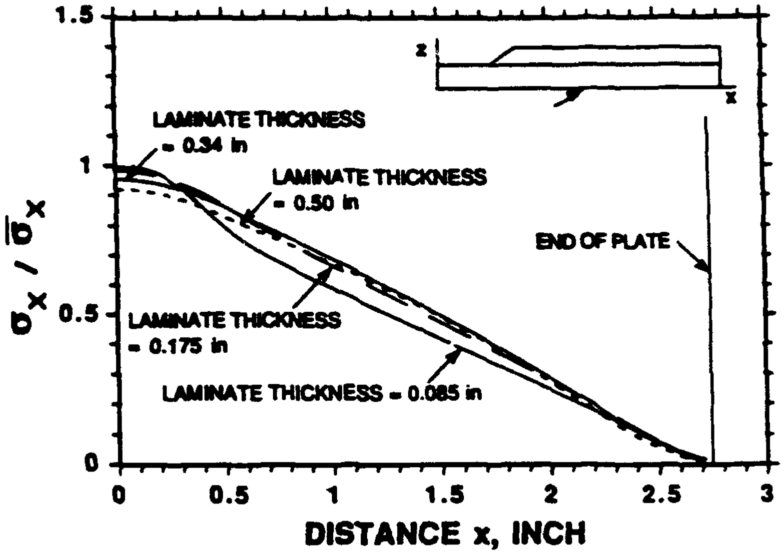


a. Applied uniform stress boundary conditions.

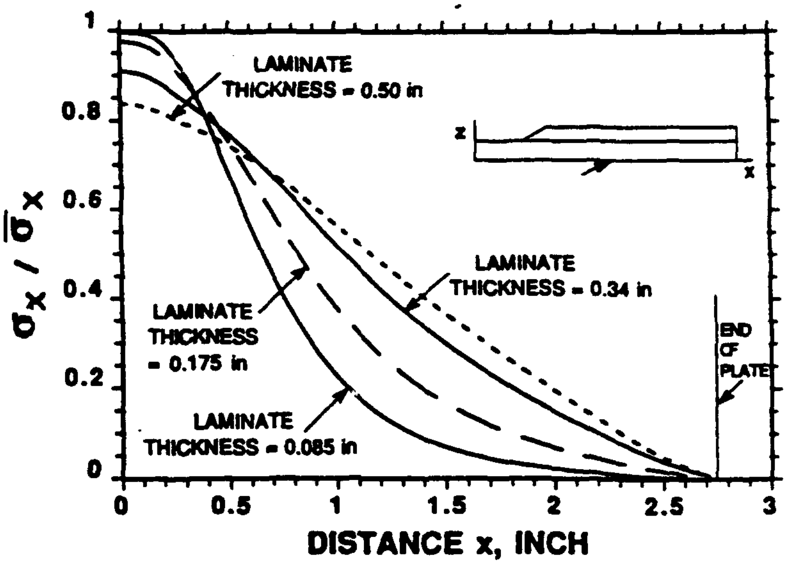


b. Applied uniform displacement.

Figure 52. Axial Stress Distributions in an AS4/3502 Carbon/Epoxy Unidirectional Composite IITRI Specimen, Through the Thickness at the Tab Tip, for Four Laminate Thicknesses [71]

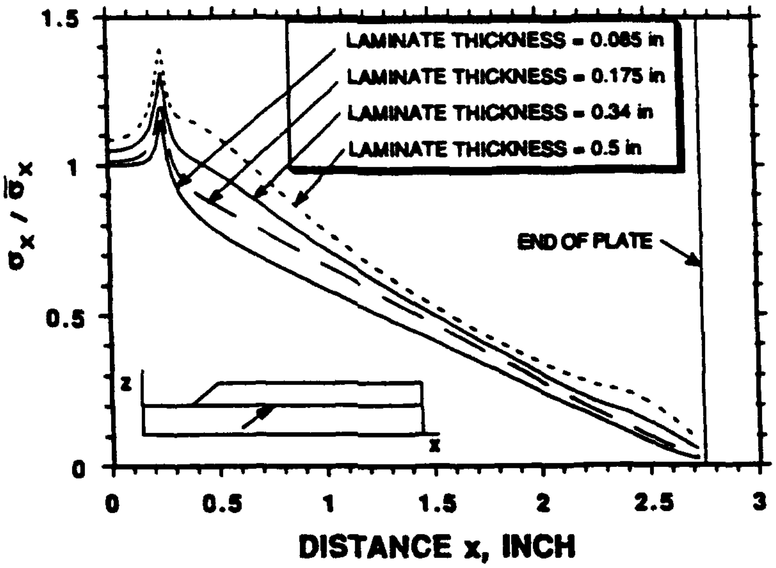


a. Applied uniform stress.

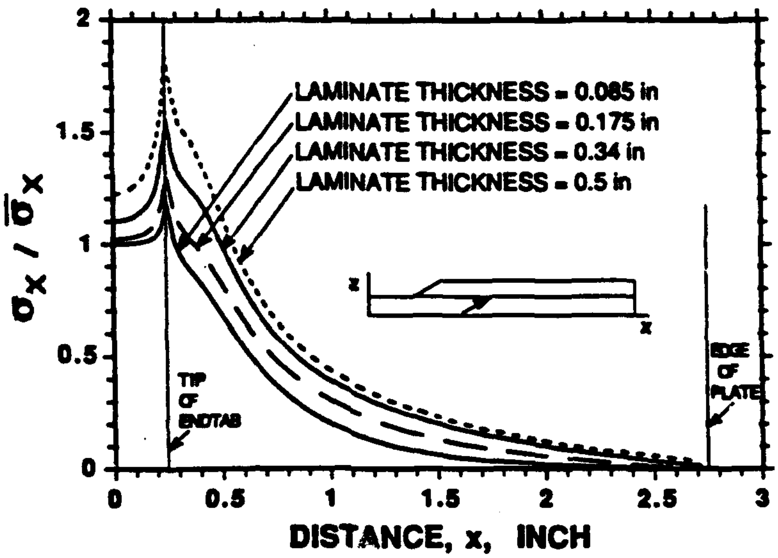


b. Applied uniform displacement.

Figure 53. Axial Stress Distributions in an AS4/3502 Carbon/Epoxy Unidirectional Composite IITRI Specimen, Along the Length of the Specimen, for Four Laminate Thicknesses [71]

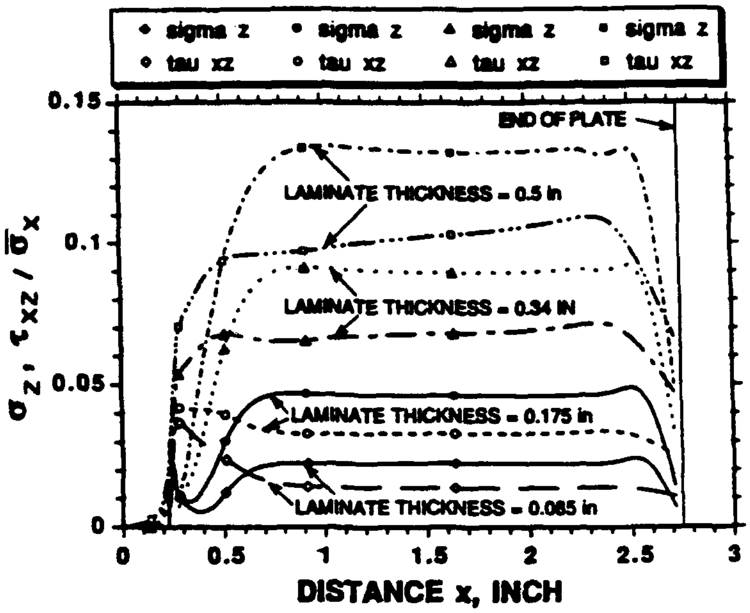


a. Applied uniform stress.

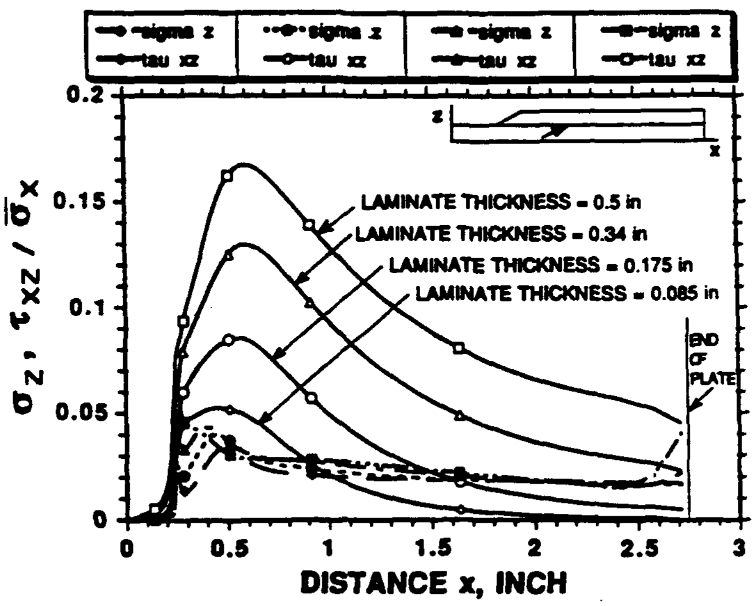


b. Applied uniform displacement.

Figure 54. Axial Stress Distributions in an AS4/3502 Carbon/Epoxy Unidirectional Composite IITRI Specimen, Along the Interface Between the Tab and Specimen, for Four Laminate Thicknesses [71]



a. Applied uniform stress.



b. Applied uniform displacement.

Figure 55. Transverse and Shear Stress Distributions in an AS4/3502 Carbon/Epoxy Unidirectional Composite IITRI Specimen, Along the Interface Between the Tab and Specimen, for Four Laminate Thicknesses [71]

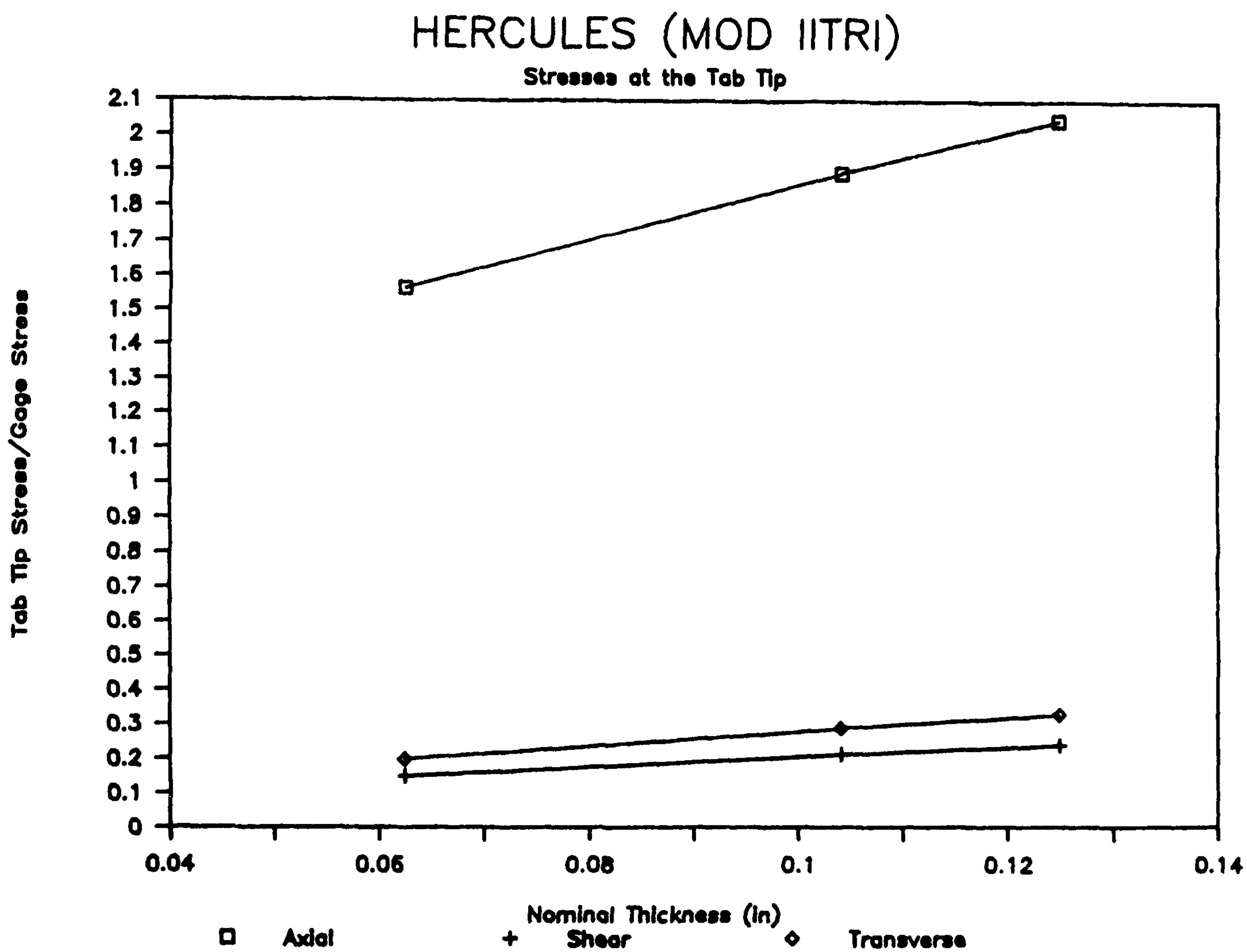


Figure 56. Peak Stresses as a Function of Specimen Thickness [12]

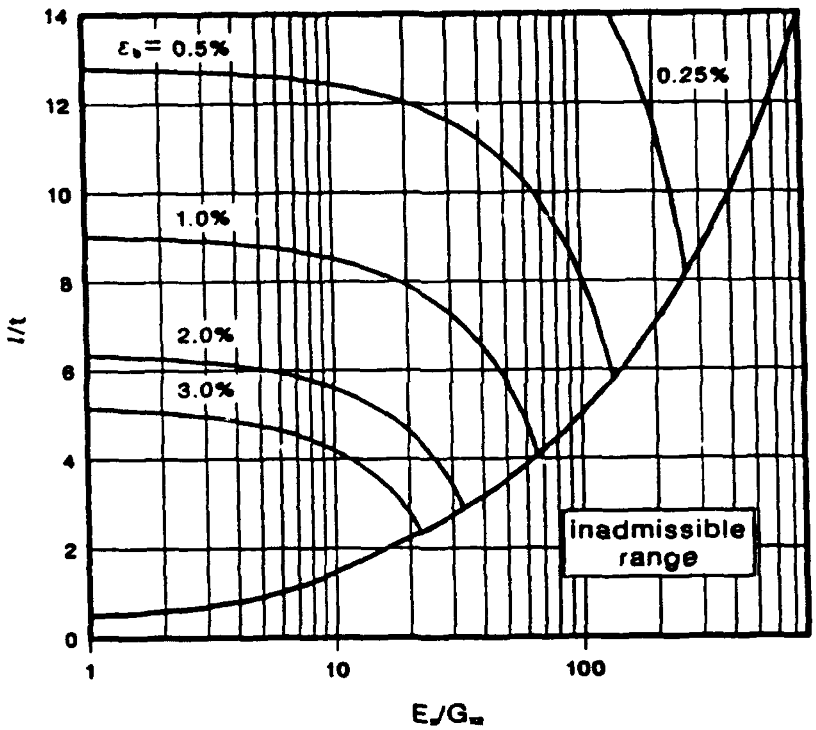


Figure 57. Specimen Design for Accurate Modulus Determination and Strength Measurement [13]

The results suggested that ASTM D3410 may not always be appropriate for materials that exhibit a high degree of orthotropy [13].

Compressive failure modes were studied in Reference [72]. Two types of eccentricities (lateral and cantilever type displacements) and two different gage lengths were assumed, as depicted schematically in Figure 58, to illustrate and evaluate the effects of specimen misalignment on the stress distribution, on the buckling load, and on the buckling shape. It was concluded that eccentricities induce bending type stresses and these stresses peak near the tabs, and compression specimens will generally fail near the tabs by a flexural type fracture mode because of a combination of compression and relatively high bending stresses in this region [72].

4.2 CELANESE SPECIMEN

The main difference between the Celanese and IITRI test methods is that the Celanese method uses conical wedge grips whereas the IITRI method uses trapezoidal wedge grips, as previously described in detail. The overall thickness of Celanese specimen is then restricted to about 0.157" (3.99 mm).

Therefore the analysis models of these two specimens are essentially the same, except the thickness of the specimen. The general results obtained for IITRI specimen can be applied to Celanese specimen.

4.3 ORIGINAL AND MODIFIED ASTM D 695 SPECIMEN

Reducing the tab taper angle from 90° to 10° correspondingly reduce all the peak stresses, however the transverse stress is reduced to greater degree than the shear stress [12].

A more compliant material used as tab material also reduces the stress concentration. Among three tab materials studied, glass/epoxy composite material is better than aluminum and graphite/epoxy composites [12].

Figure 59 presents the peak stresses at the tab tips for various tab materials and tab tapered angles.

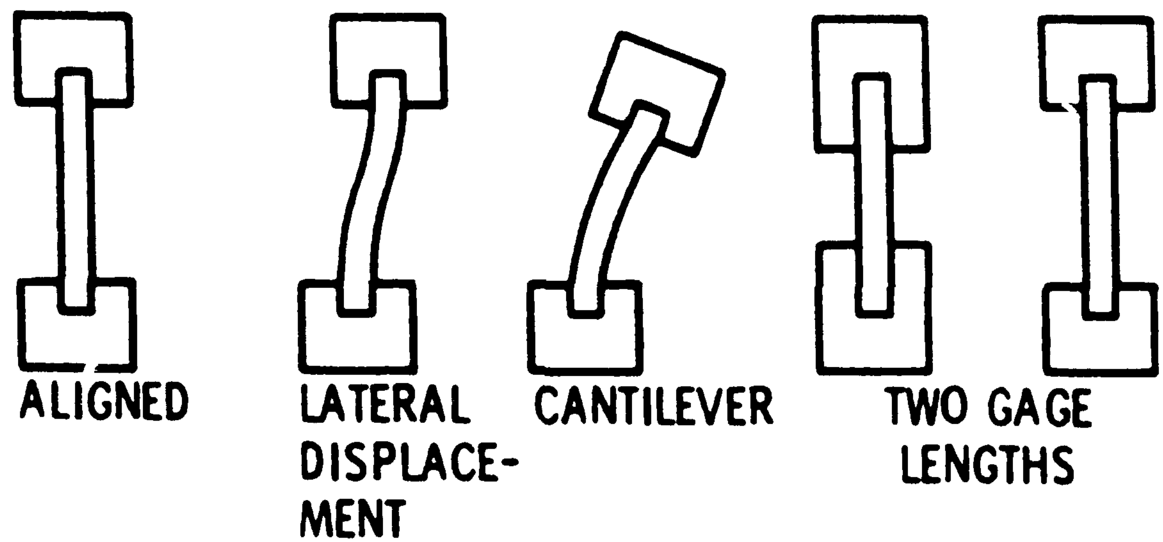


Figure 58. Schematic Depicting Eccentricities Investigated for an IITRI Specimen [72]

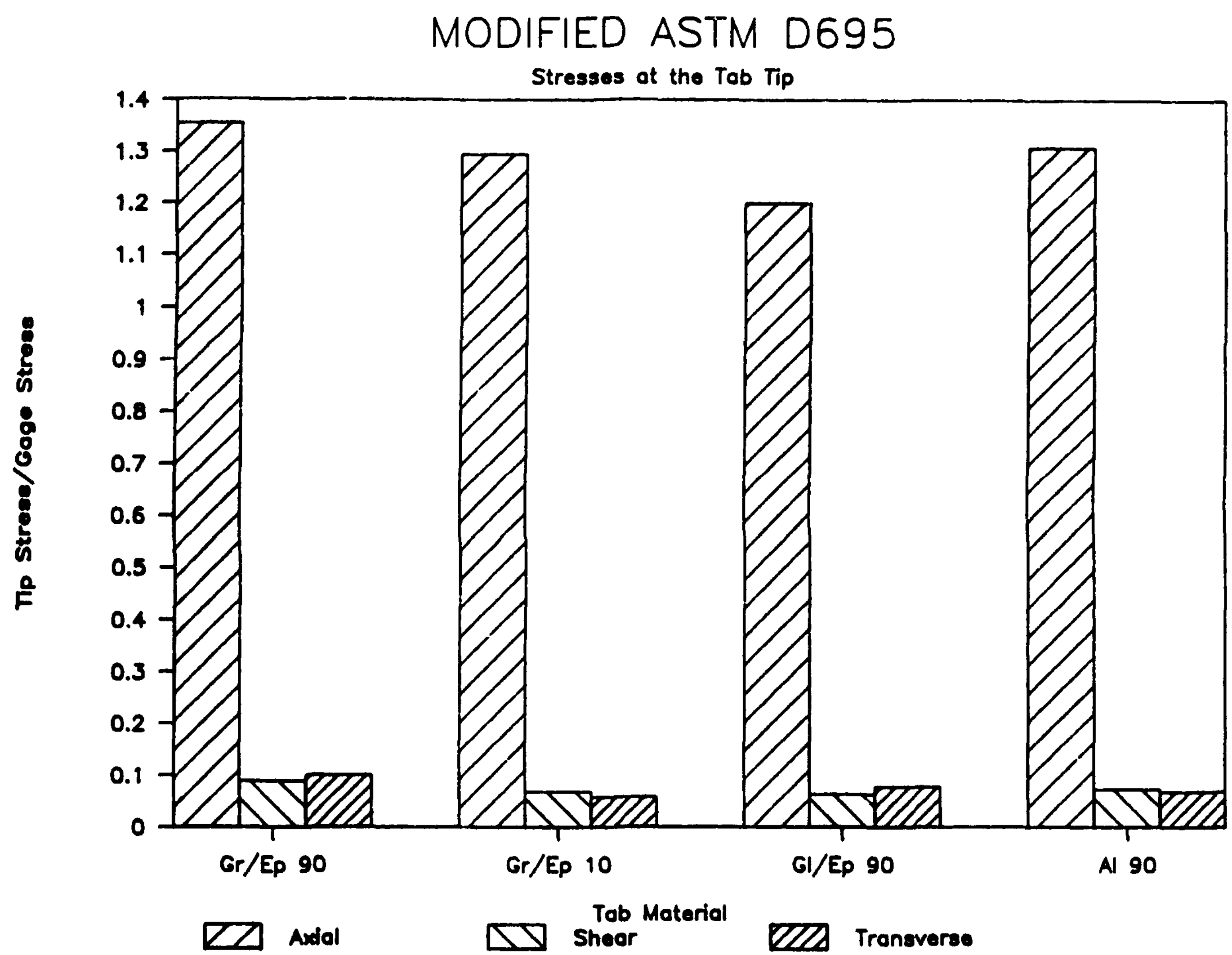


Figure 59. Peak Stresses at the Tab Tip for Various Tab Materials and Taper Angles [12]

The gage length is found to have no significant effect on the stress state in the tabbed specimen if specimen buckling is not considered [12].

When the thickness increases, the stress concentration at the tab tip becomes severe [12]. Figure 60 shows the variation of peak axial, radial, and shear stresses at the tab tips as a function of specimen thickness for the Modified ASTM D 695 specimen.

The influence of the clamping pressure (nut tightness) exerted by the face-supports on the Modified ASTM D 695 specimen is presented in Figure 61. The peak stresses dependence on nut tightness is not as predominant as it is on specimen thickness, tab material or tapered angle. In fact, while the transverse and shear stress increase with increasing clamping force on the tabs, the peak axial stress remains unchanged [12].

Other than the finite element method used in [12,45,73], some elasticity analyses are also employed to study the ASTM D 695 specimen [14,74].

A coupon specimen without tabs is investigated to quantify two effects upon the measured elastic properties of laminated composites: (a) the constrained edge effect, in which transverse expansion of the edges is prevented while the axial load is introduced; and (b) nonuniform gripping, as manifested by inplane bending of the test specimen [74].

Numerical results are presented for $[0/\pm45/90]_s$, $[\pm45]_s$, and unidirectional graphite/epoxy composite materials.

Debonding of the tabs and failure at the tab-gage juncture are found to be possible failure modes. The stress distribution through the thickness of gage section is found to be highly nonuniform [14].

4.4 RAE SPECIMEN

The RAE specimen gives a uniform longitudinal stress distribution across the specimen and negligible transverse stress (Figure 62). It is considered better than Modified ASTM D 695 specimen and Modified Celanese specimen in Reference [45].

4.5 THICK-SECTION SPECIMEN

Both end loading and side loading methods are analyzed using unidirectional composite and isotropic materials, for a 19.1 mm x 19.1 mm x 38.1 mm (0.75" x 0.75" x 1.5")

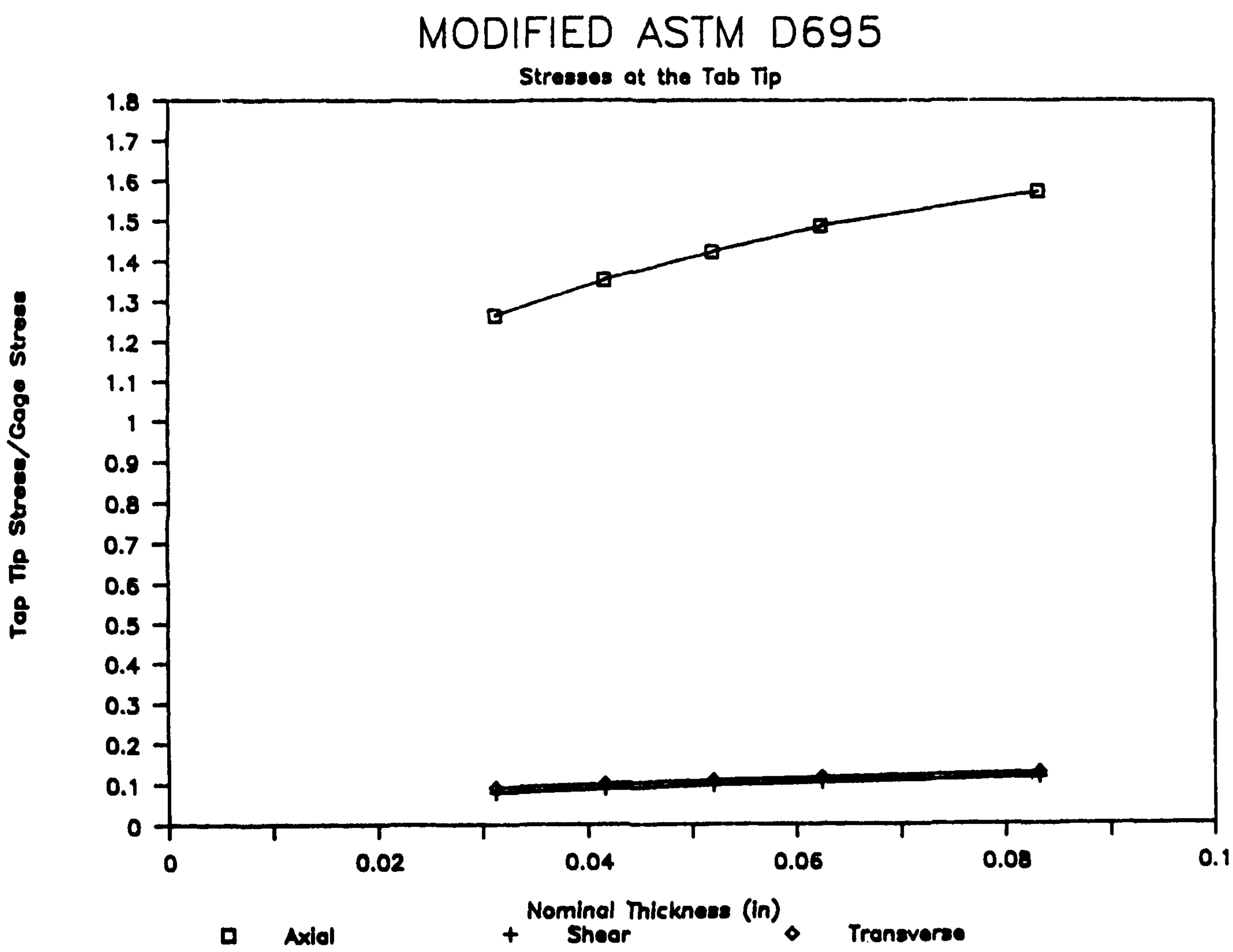


Figure 60. Peak Stresses as a Function of Specimen Thickness [12]

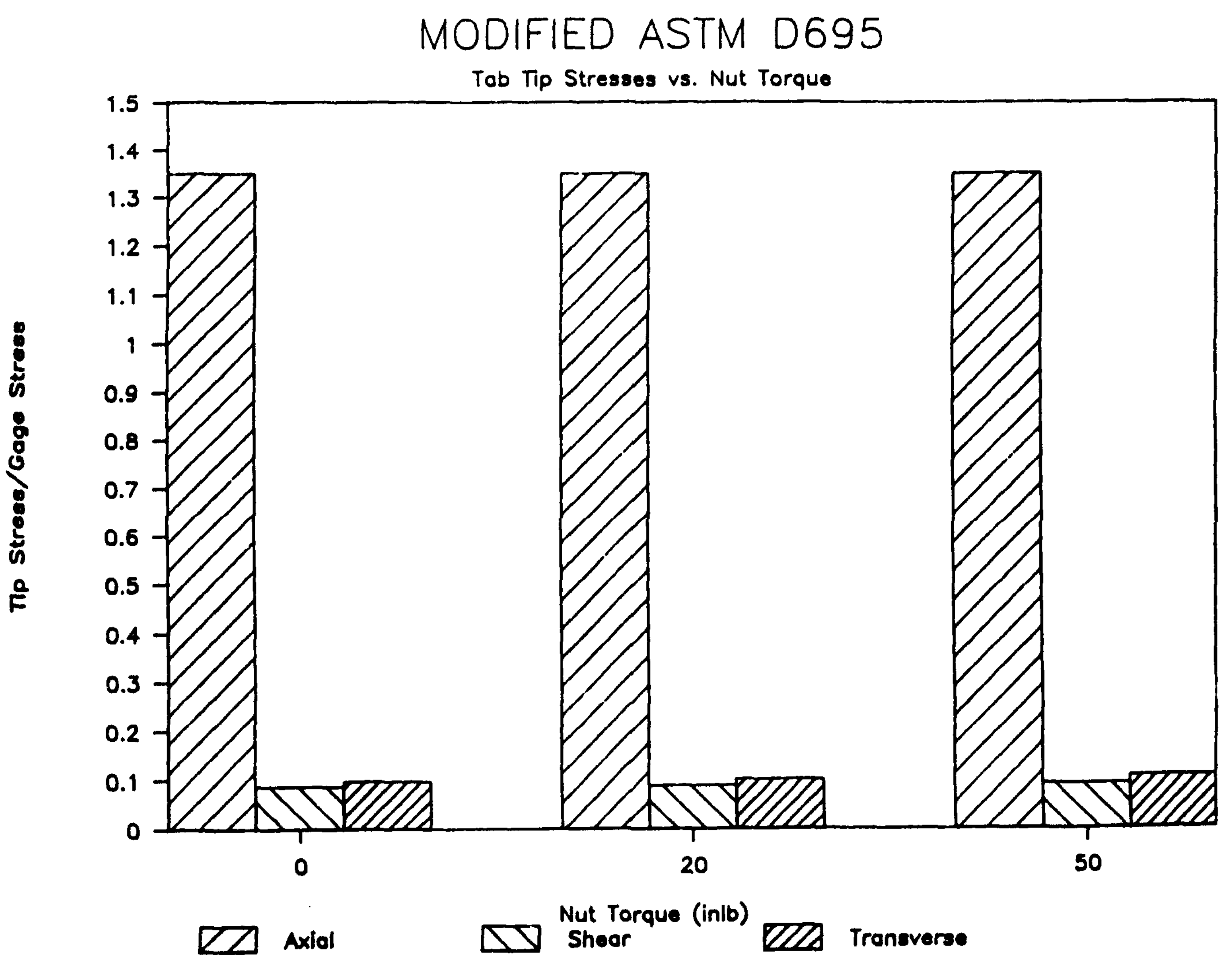
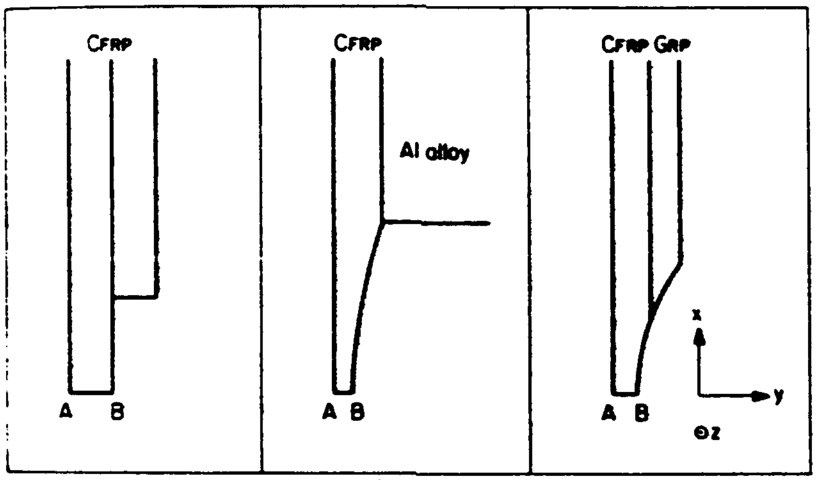


Figure 61. Peak Stresses as a function of Clamping Pressure [12]

Specimen centre section profiles (half thickness)

Modified D695 specimen	RAE specimen	Modified celanese specimen



Stresses across A–B at failure (MPa)

	σ_x	σ_y	σ_x	σ_y	σ_x	σ_y
A	-1442	-7.9	-1424	-0.4	-1574	-45
	-1442	-7.9	-1450	-1.0	-1634	-43
	-1446	-7.9	-1443	-1.0	-1781	-37
	-1447	-7.9	-1465	-1.0	-2259	-17
B	-1444	-8.4	-1490	-1.0	–	–

Figure 62. Stress Distributions in Three Compression Specimens [45]

specimen [75]. The normalized axial stress as function of the ratio of height to thickness of the specimen is shown in Figure 63. For the side loading method, isotropic and composite material end zones are 1 and 8 times that of the thickness, when the end zone is defined as a region which has one percent deviation in the uniform stress. However, for the end loading method, the normalized stress is close to 1.0 at the end (height to thickness ratio equals 0) of the specimen, i.e., the end zone for axial stress is negligible.

In end loading, the large frictional forces between the specimen and the machine cross-head tend to prevent the local failure at the ends of the specimen, thereby providing a more accurate measurement of the strength. However, for side loading method, a large gage length is required which increases the chances of buckling, and the high stress concentration at the loading end can cause failure in that region [75].

Therefore, end loading method is considered superior to side loading method for thick-section specimen [75].

A thick-section specimen with relatively small imperfection loaded by a rigid fixture can be subjected to nonuniform stress. Testing errors due to the imperfection can be eliminated if a lubricated hemispherical seat is placed under the specimen which allows the seat to rotate parallel to the specimen contact surface (Figure 64). Locking the hemispherical seat in place after self-alignment and before conducting the compression test will prevent the tilting of the seat, thereby avoiding potentially large stress variation [75].

There is a 20 percent drop in compressive strength when specimen thickness increases from 6.35 mm (0.25") to 25.4 mm (1.0") [52]. An explanation is suggested that the gage section expansion increases with specimen thickness, then so will fiber curvature, resulting in lower compressive strengths for thicker composites. The outer ply displacement geometry for three thicknesses of the AS4/3501-6 specimens is presented in Figure 65, showing an increase in the ply exit angle with increasing specimen thickness.

It is concluded that the effect of through-thickness Poisson expansion must be closely considered in areas where through-thickness restraint is present. Specially in the region of joints, the influence of through-thickness displacements become more significant with the increase of thickness alone [52].

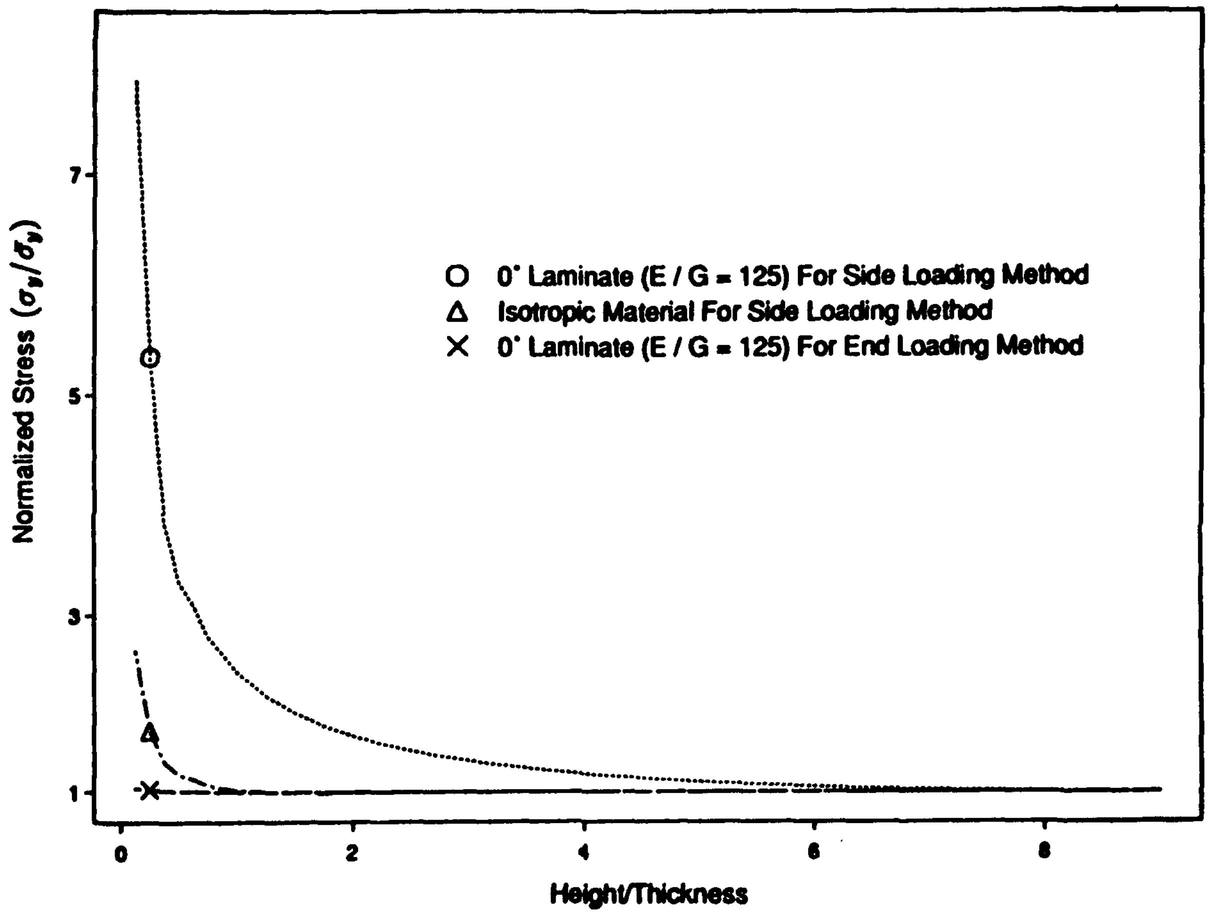


Figure 63. Effect of Loading Method on the Stress Distribution in a Thick-Section Specimen [75]

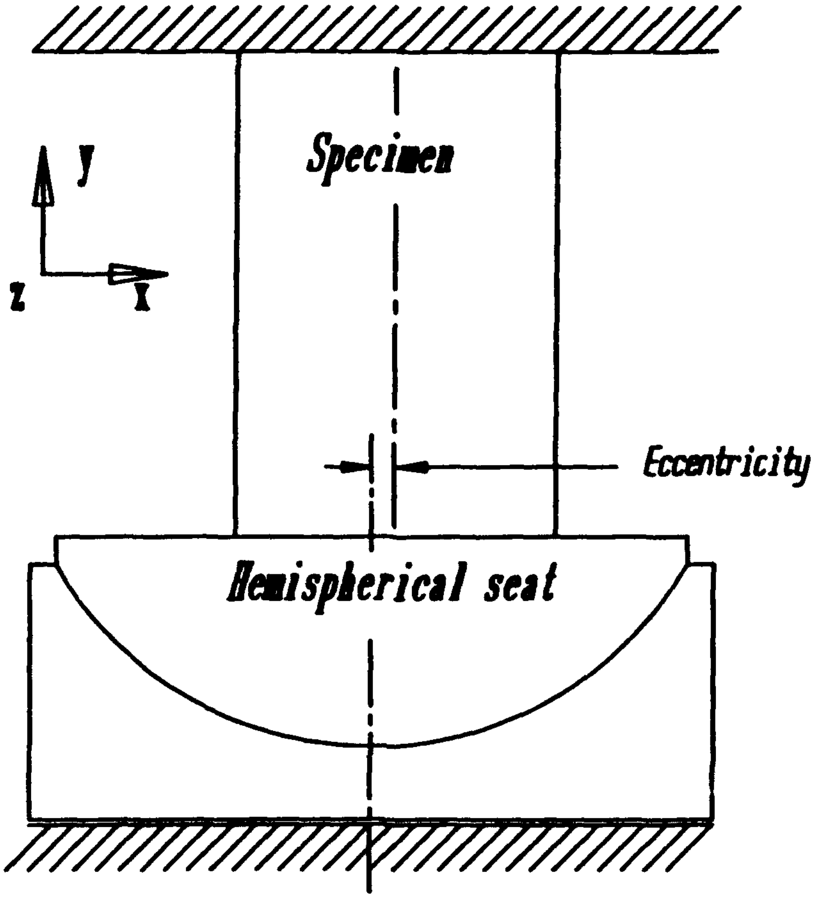


Figure 1A Sketch Of The End Loading Method

For Compression Text

Figure 64. Sketch of a Hemispherical Seat Used in Testing the End-Loaded, Thick-Section Composite Specimen [75]

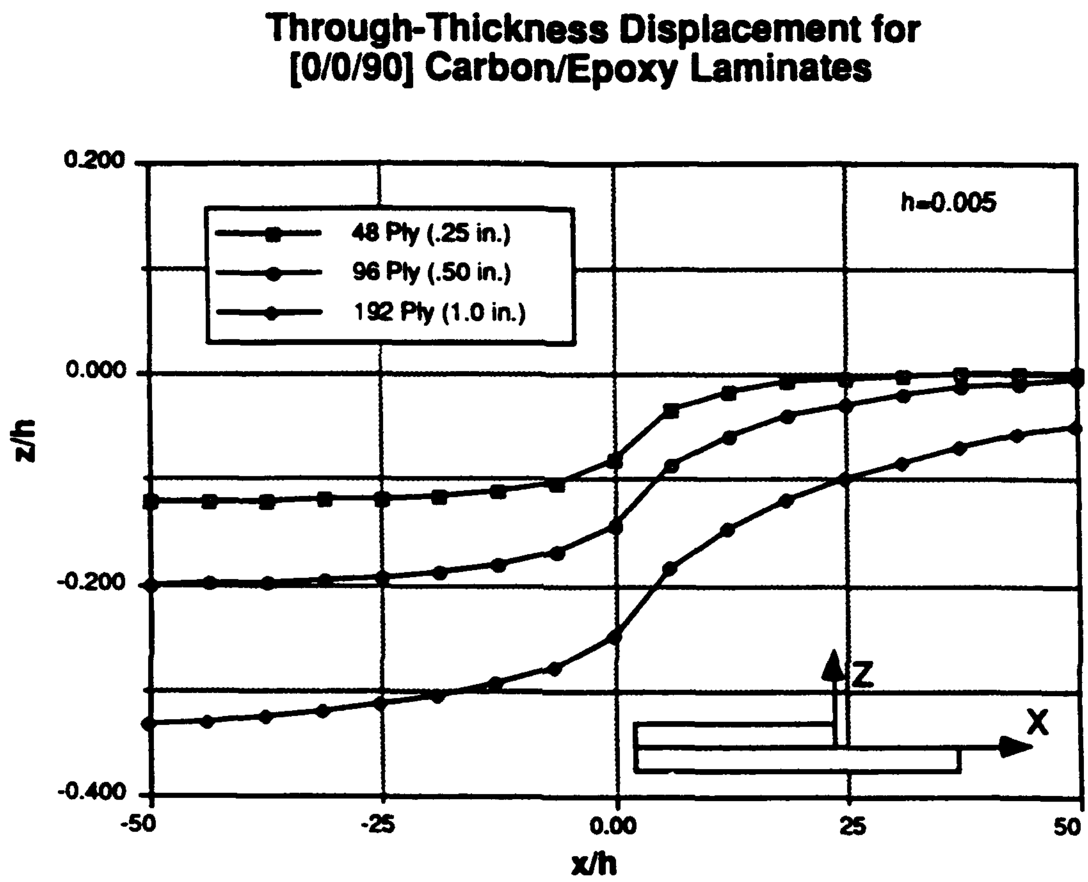


Figure 65. Outer Ply Displacement Geometry for Thick-Section AS4/3501-6 Carbon/Epoxy Cross-Ply Composite Specimens [52]

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APPENDIX

ANNOTATED BIBLIOGRAPHY

COMPRESSION TEST METHODS

(Items marked with * are also refernced in body of the report.)

APPENDIX

ANNOTATED BIBILOGRAPHY - COMPRESSION TEST METHODS

(Items marked with an * are also referenced in the body of this report)

ITEM NO. 1

AUTHORS: Abdallah, M.G.

TITLE: An Evaluation of Experimental Testing Techniques of Fiber Reinforced Composite Materials: Compression Testing Methods

SOURCE: Report No. RI 52-79: Task II, Hercules, Inc., Magna, UT

DATE: 5/31/84

TEST SPECIMENS: None

CONTENTS:

Experimental Results? [Y/N] - Y

Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - N

REMARKS: Based upon loading methods, the compression test fixtures were divided into four groups: (i) shear loaded, (ii) end-loaded, (iii) end-loaded and side-supported, and (iv) others such as sandwich beam, rings and tubes. Each method was evaluated based upon specimen configuration, test fixture, data acquisition and data interpretation. The author concluded that end-loading test methods were not suitable for producing data for product design or design allowables. He recommended the IITRI fixture and sandwich beam in four-point flexure as the best methods.

ITEM NO. 2

AUTHORS: Abdallah, M.G.

TITLE: State of the Art of Advanced Composite Materials: Compression Test Methods

SOURCE: Proceedings of JANNAF, CMCS and SAMS Joint Meeting, Jet Propulsion Lab, Pasadena, CA

DATE: November 1984

TEST SPECIMENS: None

CONTENTS:

Experimental Results? [Y/N] - Y

Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - N

REMARKS: Based upon methods of loading, test methods were classified into four groups, namely, shear-loaded, end-loaded, end-loaded and side-supported, and others such as sandwich beam, rings and tubes. Each group was evaluated based upon specimen configuration, type of fixture, data acquisition and data interpretation. The author concluded that there were no universally acceptable compression test method. He recommended the IITRI and sandwich beam in four-point bending as the best available methods. The article also includes detailed drawings and dimensions of various fixtures and specimens.

ITEM NO. 3

AUTHORS: Abdallah, M.G., Williams, T.O., and Muller, C.S.

TITLE: Experimental Mechanics of Thick Laminates: Flat Laminates Mechanical Properties Characterization

SOURCE: Report No. DDR 153253, Hercules, Inc., Magna, UT

DATE: June 29, 1990

TEST SPECIMENS: Dogbone and straight-Sided

CONTENTS:

Experimental Results? [Y/N] - Y

Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - Y

REMARKS: Dogbone and straight-sided specimens from thick laminates were tested in compression using a testing machine with hydraulic grips. The compressive

properties were sensitive to fabrication process and the thickness of the specimens. The specimen geometry also affected the compressive properties. The variation in thickness did not seem to affect the final failure modes. Finite element analysis indicated less stress concentration in the dogbone specimen compared to the straight-sided specimen.

<u>*ITEM NO. 4</u>

AUTHORS: Adams, D.F.

TITLE: A Comparison of Composite Material Compression Test Methods in Current Use

SOURCE: Proceedings of the 34th International SAMPE Symposium, Reno, Nevada

DATE: May 1989

TEST SPECIMENS: None

CONTENTS:

Experimental Results? [Y/N] - N

Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - N

REMARKS: The various compressive test methods and specific test fixtures were discussed. Different test methods were compared based upon experimental data and specific recommendations were offered.

<u>*ITEM NO. 5</u>

AUTHORS: Adams, D.F., and Lewis, E.Q.

TITLE: Influence of Specimen Gage Lengths and Loading Method on the Axial Compressive Strength of a Unidirectional Composite Material

SOURCE: Experimental Mechanics, Vol. 31, No. 1, pp. 14-20

DATE: March 1991

TEST SPECIMENS: Standard IITRI, Modified ASTM D 695

CONTENTS:

Experimental Results? [Y/N] - Y

Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - N

REMARKS: The above mentioned two test methods were compared by testing a unidirectional graphite/epoxy composite material. Specimens with different gage lengths were also tested using the IITRI fixture. Both the test methods produced similar modulus and strength data as long as end crushing and tab debonding were avoided. Variation in gage length had negligible influence on strength as long as gross buckling was avoided.

***ITEM NO. 6**

AUTHORS: Adams, D.F., and Odom, E.M.

TITLE: Influence of Specimen Tabs on the Compressive Strength of a Unidirectional Composite Material

SOURCE: Journal of Composite Materials, Vol. 25, pp. 774-786

DATE: June 1991

TEST SPECIMENS: Standard IITRI with tapered and untapered steel and glass-fabric/epoxy tabs

CONTENTS:

Experimental Results? [Y/N] - Y

Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - N

REMARKS: Specimens with tapered or untapered steel tabs produced nearly equal compressive strengths inspite of full or partial grip by the fixture. Fully gripped specimens with tapered glass-fabric/epoxy tabs produced lower compressive strengths. Stiffer steel tabs were assumed to provide sufficient specimen stability even when the specimens were not fully gripped. Steel tabbed specimens from a second laminate of the same material showed the same trend; however, the compressive strengths obtained from the second panel were higher than those from the first panel.

The tapered glass-fabric/epoxy tab configuration from second panel resulted in lower strengths and was observed to buckle. However, the untapered glass-fabric/epoxy tabbed specimens resulted in nearly equal strengths as exhibited by steel tabbed specimens. Deliberately introduced tab debonding resulted only in very small reduction in compressive strengths.

***ITEM NO. 7**

AUTHORS: Adams, D.F., and Odom, E.M.

TITLE: Influence of Test Configuration on the Measured Compressive Strength of a Composite Material

SOURCE: Journal of Composites Technology & Research, Vol. 13, No. 1, pp. 36-40

DATE: Spring 1991

TEST SPECIMENS: Standard IITRI, Wyoming Modified Celanese and Wyoming Modified IITRI

CONTENTS:

Experimental Results? [Y/N] - Y

Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - N

REMARKS: Three compression test fixtures were compared by testing AS4/3501-6 carbon/epoxy composites. Specimens were tabbed with either tapered steel or untapered glass-fabric/epoxy tabs. For the steel tabbed specimens, IITRI and Wyoming Modified Celanese fixtures produced similar compressive strengths whereas Wyoming Modified IITRI fixture produced lower strengths. For the glass-fabric/epoxy tabbed specimens, all three fixtures produced nearly equal strengths which were comparable to the strengths of the steel tabbed specimens. All three fixtures also produced similar modulus values.

***ITEM NO. 8**

AUTHORS: Adsit, N.R.

TITLE: Compression Testing of Graphite/Epoxy

SOURCE: Compression Testing of Homogeneous Materials and Composites, ASTM STP 808, R. Chait and R. Papirno, Eds., American Society for Testing and Materials, Philadelphia, Pa, pp.175-186

DATE: 1983

TEST SPECIMENS: ASTM D 695, Celanese, IITRI and sandwich beam

CONTENTS:

Experimental Results? [Y/N] - Y

Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - Y

REMARKS: Compressive moduli were independent of the loading method within experimental scatter. ASTM D 695 specimens exhibited lower strengths than the other specimens. The end-loaded specimens failed by delamination or shear. The strength data obtained from IITRI, Celanese and sandwich beam methods were similar within statistical error. However, there was great discrepancy in strength data reported by different investigators testing the same material in identical fixtures.

***ITEM NO. 9**

AUTHORS: Barker, A.J., and Balasundaram, V.

TITLE: Compression Testing of Carbon-Reinforced Plastics Exposed to Humid Environments

SOURCE: Composites, Vol. 18, No. 3, pp. 217-226

DATE: July 1987

TEST SPECIMENS: Rectangular, waisted and unwaisted, untabbed specimens fabricated from unidirectional and multidirectional laminates

CONTENTS:

Experimental Results? [Y/N] - Y

Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - Y

REMARKS: A compression fixture in which rectangular specimens were held by side face clamps in steel blocks was designed. The steel blocks were placed

within high precision die set to ensure axial loading. The specimens were loaded through the ends as well as through the side clamps. The maximum gage length possible without incurring gross buckling was predicted by an analysis which included several failure criteria. The new fixture was found suitable for environmental testing. Untabbed, waisted, unidirectional specimens tested in this fixture produced strengths comparable to those of tabbed unwaisted specimens.

***ITEM NO. 10**

AUTHORS: Bazhenov, S.L., and Kozey, V.V.

TITLE: Compression Fracture of Unidirectional Carbon Fibre-Reinforced Plastics

SOURCE: Journal of Materials Science, Vol. 26, pp. 6764-6776

DATE: 1991

TEST SPECIMENS: Cylindrical dogbone, rectangular IITRI type, fiber strands glued to elastic beam, fiber loop

CONTENTS:

Experimental Results? [Y/N] - Y
Analytical Results? [Y/N] - N
Failure Mode Info? [Y/N] - Y

REMARKS: Three epoxy resins reinforced with different PAN-based carbon fibers were tested in compression using the dogbone and rectangular specimens. The compressive strengths of the fibers were also calculated by three-point and four-point bending of fiber strands glued to elastic beams as well as the loop method. IITRI type specimens with circular holes were also tested. The paper also provides brief information on the effect of temperature and interfacial adhesion on compressive strength. Failure was attributed to fiber kinking. Discrepancy in the strengths measured by bending and loop method was reported. The dependence of composite strength on fiber compressive strength was also studied.

__*ITEM NO. 11__

AUTHORS: Bazhenov, S.L., Kozey, V.V., and Berlin, A.A.

TITLE: Compression Fracture of Organic Fiber Reinforced Plastics

SOURCE: Journal of Materials Science, Vol. 24, pp. 4509-4515

DATE: 1989

TEST SPECIMENS: Cylindrical rods, rectangular coupons, rings

CONTENTS:

Experimental Results? [Y/N] - Y

Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - Y

REMARKS: Epoxy reinforced with organic fibers (PABI and PPT) were tested in compression using the above mentioned specimen geometry. Compressive modulus was found to be proportional to the fiber content. The fiber compressive strength was estimated from the flexure of the ring specimens. The compressive strengths of both composites were almost identical inspite of different test methods and different fiber properties. Three modes of plastic deformation leading to failure was postulated. At high temperature, loss of fiber stability was suspected. The compressive strength was found to be insensitive to the presence of notch or hole in the composite.

__ITEM NO. 12__

AUTHORS: Beck, A.R., and Yen, A.

TITLE: Development of Ultralightweight Materials. Fourth Quarterly Interim Technical Report

SOURCE: Report No. NOR 89-66, Contract No. F33615-88-C5447, Northrop Corporation, Hawthorne, CA

DATE: May 1989

TEST SPECIMENS: None

CONTENTS:

Experimental Results? [Y/N] - N

Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - N

REMARKS: This report included a literature review of composite compressive properties. It included detailed discussions on microbuckling, fiber kinking, matrix yield theories and rule of mixtures. It also included experimental information on some methods.

***ITEM NO. 13**

AUTHORS: Berg, J.S., and Adams, D.F.

TITLE: An Evaluation of Composite Material Compression Test Methods.

SOURCE: Journal of Composites Technology & Research, Vol. 11, No. 2, pp. 41-46

DATE: Summer 1989

TEST SPECIMENS: Standard IITRI, Wyoming Modified Celanese, Wyoming end-loaded side-supported

CONTENTS:

Experimental Results? [Y/N] - Y

Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - N

REMARKS: Unidirectional and quasi-isotropic laminates of glass/epoxy and carbon/epoxy were tested using the above mentioned fixtures. The IITRI fixture produced the highest compressive strength and the lowest compressive modulus. The Wyoming Modified Celanese fixture also produced statistically similar results. However, the end-loaded fixture resulted in reduced strength due to end crushing and splitting. It also produced, sometimes, misleading high modulus values due to the frictional loading of the fixture guide pins. Strain measurement by extensometers and strain gauges gave comparable results.

***ITEM NO. 14**

AUTHORS: Bethony, W.M., Nunes, J., and Kidd, J.A.

TITLE: Compressive Testing of Metal Matrix Composites

SOURCE: Testing Technology of Metal Matrix Composites, ASTM STP 964, P.R. DiGiovanni and N.R. Adsit, Eds., American Society for Testing and Materials, Philadelphia, PA, pp. 319-328

DATE: 1988

TEST SPECIMENS: End-loaded cylindrical and square cross-section, tabbed IITRI specimens

CONTENTS:

Experimental Results? [Y/N] - Y

Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - Y

REMARKS: A modified version of the compressive fixture as designed by Lamothe and Nunes was used to test metal-matrix composites. Results were compared to those obtained by using an IITRI fixture. The cylindrical specimens tested in the new fixture produced satisfactory results with low scatter. However, the square specimens failed by premature brooming. For the IITRI specimens, a better technique had to be developed to adhere aluminum tabs to the specimens. The IITRI fixture produced data with significant amount of scatter.

***ITEM NO. 15**

AUTHORS: Bogetti, T.A., Gillespie, Jr., J.W., and Pipes, R.B.

TITLE: Evaluation of the IITRI Compression Test Method for Stiffness and Strength Determination

SOURCE: Composites Science and Technology, Vol.32, pp. 57-76

DATE: 1988

TEST SPECIMENS: IITRI

CONTENTS:

Experimental Results? [Y/N] - N

Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - N

REMARKS: The influence of material anisotropy and specimen geometry on the experimental results was examined. The study utilized a two-dimensional linear finite element analysis and an elasticity solution based on Saint-Venant's principle for an upper bound estimate on stress decay length in a parametric study involving combinations of specimen geometries with varying material anisotropy. A methodology was presented for sizing specimen geometries as a function of material anisotropy.

***ITEM NO. 16**

AUTHORS: Camponeschi Jr, E.T.

TITLE: Compression Response of Thick-Section Composite Materials

SOURCE: Report No. DTRC-SME-90/60, David Taylor Research Center, Bethesda, MD

DATE: October 1990

TEST SPECIMENS: End-Loading Thick Specimen

CONTENTS:

Experimental Results? [Y/N] - Y

Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - Y

REMARKS: The response of composite materials between 0.25 and 1.0 in. thick was investigated. The effect of thickness on elastic properties, strength, and failure mechanism was examined experimentally and theoretically. Both two- and three-dimensional linear finite element analyses were employed.

***ITEM NO. 17**

AUTHORS: Camponeschi, Jr., E.T.

TITLE: Compression of Composite Materials: A Review

SOURCE: Report No. DTRC-87/050, David Taylor Research Center, Bethesda, MD

DATE: November 1987

TEST SPECIMENS: None

CONTENTS:

Experimental Results? [Y/N] - N

Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - Y

REMARKS: This was a review of literature on compressive response of fiber-reinforced composite materials. The three main topics discussed in the review were compression test methods, failure theories and mechanisms, and experimental investigations. Emphasis was on publications from 1980 to 1987.

ITEM NO. 18

AUTHORS: Camponeschi, Jr., E.T.

TITLE: Compression of Composite Materials: A Review

SOURCE: Report No. CCM 87-40, Center for Composite Materials, College of Engineering, University of Delaware, Newark, DE

DATE: August 1987

TEST SPECIMENS: None

CONTENTS:

Experimental Results? [Y/N] - N

Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - Y

REMARKS: This report was same as report no. DTRC-87/050 of David Taylor Research Center.

***ITEM NO. 19**

AUTHORS: Chamis, C.C., and Sinclair, J.H.

TITLE: Longitudinal Compressive Failure Modes in Fiber Composites: End Attachment Effects on IITRI Type Test Specimen

SOURCE: Journal of Composites Technology & Research, Vol.7, No.4, pp. 129-135

DATE: Winter 1985

TEST SPECIMENS: IITRI

CONTENTS:

Experimental Results? [Y/N] - Y

Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - Y

REMARKS: The end tab effects on compressive strength of IITRI type specimen were assessed using a three-dimensional linear finite element analysis in conjunction with composite mechanics. Sixteen different cases were analyzed to evaluate end-tab effects on stress state, peak stresses, buckling load, and buckling mode shapes, such as degree of misalignment, type of misalignment, progressive tab debonding, and specimen thickness. The analysis results were compared with experiments.

***ITEM NO. 20**

AUTHORS: Chen, T.K.

TITLE: Compression Test Simulation of Thick-Section Composite Materials

SOURCE: Report No. AMTL-TR-92-25, U.S. Army Materials Technology Laboratory, Watertown, MA

DATE: 1992

TEST SPECIMENS: End-Loading Thick Specimen

CONTENTS:

Experimental Results? [Y/N] - N

Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - N

REMARKS: A finite element model was used to evaluate compression test methods for thick-section composite materials. Both two- and three-dimensional linear analysis were carried out, but there was no significant difference in the results. An end loaded specimen supported by a locked hemispherical seat was determined to be the most desirable than the side loading method for the thick composites since it provided uniform stress field in the specimen.

The locked hemispherical seat eliminated the stress concentration due to specimen imperfection while providing the necessary support for the specimen by preventing a tilt action due to eccentricity.

***ITEM NO. 21**

AUTHORS: Clark, R.K., and Lisagor, W.B.

TITLE: Compression Testing of Graphite/Epoxy Composite Materials

SOURCE: Test Methods and Design Allowables for Fibrous Composites, ASTM STP 734, C.C. Chamis, Ed., American Society for Testing and Materials, Philadelphia, PA, pp. 34-53

DATE: 1981

TEST SPECIMENS: Modified IITRI, face supported and end-loaded specimens

CONTENTS:

Experimental Results? [Y/N] - Y

Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - Y

REMARKS: Unidirectional, quasi-isotropic and cross-ply specimens were tested. Four strain gages were used to measure strain in each specimen. Flat and parallel specimens were necessary to avoid strain variations due to out-of-plane and inplane bending. Higher strain variations resulted in reduced compressive strengths in unidirectional specimens. Compressive strength was found to be sensitive to specimen width in case of unidirectional specimens, but not in the case of quasi-isotropic and cross-ply specimens. The IITRI fixture produced higher strength data compared to the face-supported and end-loaded fixture. The compressive secant modulus was not sensitive to the variation in the specimen width, except in the case of cross-ply specimens. In the IITRI fixture, unidirectional specimens failed near the tabs whereas quasi-isotropic and cross-ply specimens failed in the gage sections. End-loaded quasi-isotropic specimens failed in the gage sections without end brooming. However, detailed study of failure modes was not provided in the paper.

***ITEM NO. 22**

AUTHORS: Crasto, A.S., and Kim, R.Y.

TITLE: Compression Strengths of Advanced Composites from a Novel Mini-Sandwich Beam

SOURCE: SAMPE Quarterly, Vol. 22, No. 3, pp. 29-39

DATE: April 1991

TEST SPECIMENS: Mini-sandwich beam

CONTENTS:

Experimental Results? [Y/N] - Y

Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - Y

REMARKS: A mini-sandwich beam with a neat resin core consolidated together with the laminate skins was tested in four-point flexure and in axial compression in an IITRI fixture. For the specimens with brittle epoxy core, the IITRI method produced consistently higher strengths than four-point flexure. However, for specimens with thermoplastic core, four-point flexure produced higher strengths. Strengths obtained from these two methods were higher than the values obtained by testing standard coupons in an IITRI fixture. Skins consisting of 2 to 4 plies were recommended. Skin fracture accompanied by delamination and core-cracking was observed. Skin buckling was observed in some specimens.

***ITEM NO. 23**

AUTHORS: Curtis, P.T., Gates, J., and Molyneux, C.G.

TITLE: An Improved Engineering Test Method for Measurement of the Compressive Strength of Unidirectional Carbon Fiber Composites

SOURCE: Composites, Vol. 22, No. 5, pp. 363-368

DATE: September 1991

TEST SPECIMENS: RAE modified Celanese, tabbed and untabbed with or without face-waisted gage section

CONTENTS:

Experimental Results? [Y/N] - Y

Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - Y

REMARKS: Untabbed specimens were prepared from laminates with a central core of unidirectional plies with equal number of ±45° plies on both side of the core. Some of these specimens were face-waisted by machining off the ±45° plies. Standard tabbed unidirectional specimens were also tested. Untabbed face-waisted specimens produced higher compressive strengths than the standard tabbed specimens. Untabbed unwaisted specimens produced lower failure stress. However, a rule of mixture approach to calculate failure stress in the 0° plies produced compressive strengths even higher than those of the face-waisted specimens. The compressive strength is also sensitive to machining to prepare the face-waisted specimens. Fiber kinking was observed in the waisted specimens, all of which failed in the gage section. Delamination between the continuous and discontinuous unidirectional layers at the waist of the specimens was observed.

***ITEM NO. 24**

AUTHORS: Ewins, P.D.

TITLE: A Compressive Test Specimen for Unidirectional Carbon Fiber Reinforced Plastics

SOURCE: Technical Report C.P. No. 1132, Structures Department, Royal Aircraft Establishment, Farnborough, U.K.

DATE: January 1970

TEST SPECIMENS: Circular waisted rods with tapered end caps of steel

CONTENTS:

Experimental Results? [Y/N] - Y

Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - N

REMARKS: The gage section of the specimen was waisted to about 80 percent of the nominal diameter to ensure failure in the test section. Specimen ends were glued into the hole of the tapered end caps. The ends of the caps were machined flat. The compressive strength increased with increasing fiber volume fraction. A two dimensional model based upon fiber buckling theory was utilized to predict compressive strength. There was a big difference between the predicted and experimental values.

***ITEM NO. 25**

AUTHORS: Ewins, P.D.

TITLE: Tensile and Compressive Test Specimens for Unidirectional Carbon Fibre Reinforced Plastics

SOURCE: Technical Report 71217, Royal Aircraft Establishment, Farnborough, U.K.

DATE: November 1971

TEST SPECIMENS: Rectangular, thickness-waisted specimens with aluminum end fittings

CONTENTS:

Experimental Results? [Y/N] - Y

Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - Y

REMARKS: A new specimen configuration was designed to ensure failure in the gage section. The rectangular specimen was waisted in the thickness direction. The ends of the specimen were bonded into accurately machined slots of the aluminum alloy end fittings. The specimen was loaded on the ends as well as by shear at the bonded joint. An analysis was performed to calculate the maximum allowable taper angle of the specimen. A similar configuration with reduced taper angle and gage length was also tested in transverse compression. Improved compressive strengths were obtained. All the specimens failed in the expected manner without any evidence of end effects.

***ITEM NO. 26**

AUTHORS: Gedney, C., Pascual, C., Kolkailah, F., and Wilson, B.

TITLE: Comparison of ASTM Standard Compression Test Methods of Graphite/Epoxy Composite Specimens

SOURCE: Proceedings of the 32nd International SAMPE Symposium, pp. 1015-1024

DATE: April 1987

TEST SPECIMENS: ASTM D 695, Modified ASTM D 695, Celanese

CONTENTS:

Experimental Results? [Y/N] - Y

Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - N

REMARKS: Three test methods, namely, ASTM D 695, Modified ASTM D 695 (Tabbed and Untabbed) were examined. The ultimate compressive strength and simplicity of each test method were measured and observed. A three-dimensional linear finite element analysis was used to model ASTM D 695 and Modified ASTM D 695 specimens. It was found that the Modified ASTM D695 with tabbed specimen yielded the most accurate results with the least amount of effort.

ITEM NO. 27

AUTHORS: Greszczuk, L.B.

TITLE: Failure Mechanics of Composites Subjected to Compressive Loading

SOURCE: Report No. AFML-TR-72-107, Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio.

DATE: August 1972

TEST SPECIMENS: Columns with rectangular cross-sections, circular rod clusters with encapsulated ends

CONTENTS:

Experimental Results? [Y/N] - Y

Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - Y

REMARKS: For rectangular specimens reinforced with aluminum strips, the effect of variables such as laminae volume fraction, laminae thickness, specimen geometry, matrix properties and laminae end configuration on compressive strength was investigated theoretically and experimentally. For circular rod clusters reinforced with circular rods of aluminum, steel and graphite, the influence of factors such as fiber array, fiber diameter, fiber volume fraction, specimen geometry, constituent properties and initial imperfections on compressive strength was studied. A theory to predict compressive microbuckling strength was derived and verified experimentally. Failure modes for both types of reinforcement were also studied.

***ITEM NO. 28**

AUTHORS: Gruber, M.B., Overbeeke, J.L., and Chou, T.-W.

TITLE: A Reusable Sandwich Beam Concept for Composite Compression Test

SOURCE: Journal of Composite Materials, Vol. 16, pp. 162-171

DATE: May 1982

TEST SPECIMENS: Tabbed rectangular coupon on reusable sandwich beam, IITRI

CONTENTS:

Experimental Results? [Y/N] - Y

Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - Y

REMARKS: The sandwich beam fixture consisted of a plexiglass core in the test section and aluminum core in the ends. Graphite/epoxy laminates were used as the tension face. The test coupon, a rectangular bar with tapered tabs on one face, was clamped onto the beam. An analysis was performed to study the beam subjected to four-point bending. The modulus data on glass composites from the beam and IITRI methods agreed, within the range of experimental error. In case Kevlar/glass hybrids, the beam method produced higher modulus values than the IITRI method. The beam method also produced slightly higher strength data. The hybrid specimens failed in shear in both methods. The glass composite failed by fiber kinking.

***ITEM NO. 29**

AUTHORS: Gürdal, Z., and Starbuck, J. M.

TITLE: Compressive Characterization of Unidirectional Composite Materials

SOURCE: Proceedings of Analytical and Testing Methodologies for Design with Advanced Materials, Montreal, Canada.

DATE: August 24-26, 1987

TEST SPECIMENS: End-loaded coupon supported by four circular side support pins

CONTENTS:

Experimental Results? [Y/N] - Y

Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - N

REMARKS: A new compression test fixture featuring four circular pins providing side support to an end-loaded coupon was used to test 0°, 90° and off-axis laminates of different materials. A 2-D finite element code was utilized to perform a stress analysis on the coupons to account for a nonuniform and bidirectional stress state in the gage section.

***ITEM NO. 30**

AUTHORS: Ha, J.-B., and Nairn, J.A.

TITLE: Compression Failure Mechanisms of Single-Ply Unidirectional, Carbon-Fiber Composites

SOURCE: SAMPE Quarterly, Vol. 23, No. 3, pp. 29-36

DATE: April 1992

TEST SPECIMENS: Dogbone shaped single ply embedded in transparent epoxy

CONTENTS:

Experimental Results? [Y/N] - Y

Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - Y

REMARKS: The dependence of composite compressive strength on fiber type, matrix type and interfacial adhesion was studied. Low modulus carbon fiber composites had a higher strength compared to high modulus carbon fibers.

Higher modulus epoxy matrix composites had a higher compressive strengths than lower modulus thermoplastic matrix composites. Compressive strength was found to be sensitive to interfacial bond strength; however, no correlation between the two was established. Fiber sizing had no effect on the compressive strength as well as failure modes. Failures in the various composites were attributed to fiber kinking, out-of-plane slip and longitudinal splitting. However, the sequence of initiation of different failure modes could not be resolved due to catastrophic nature of the failure event.

ITEM NO. 31

AUTHORS: Hahn, H.T., and Sohi, M.M.

TITLE: Buckling of a Fiber Bundle Embedded in Epoxy

SOURCE: Composites Science and Technology, Vol.27, pp. 25-41

DATE: 1986

TEST SPECIMENS: Fiber bundle embedded in epoxy, IITRI fixture

CONTENTS:

Experimental Results? [Y/N] - Y

Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - Y

REMARKS: Bundles of PAN as well as pitch-based carbon fibers and glass fibers embedded in epoxy were tested in an IITRI compression fixture. Pan-based carbon fibers and glass fibers failed in buckling while pitch-based carbon fibers failed in shear. Pan-based carbon fibers also exhibited fiber kinking.

***ITEM NO. 32**

AUTHORS: Hahn, H.T., and Williams, J.G.

TITLE: Compression Failure Mechanisms in Unidirectional Composites

SOURCE: Composite Materials: Testing and Design (Seventh Conference), ASTM STP 893, J.M. Whitney, Ed., American Society for Testing and Materials, Philadelphia, PA, pp. 115-139

DATE: 1986

TEST SPECIMENS: IITRI (ASTM D 3410-82)

CONTENTS:

Experimental Results? [Y/N] - Y

Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - Y

REMARKS: Seven unidirectional graphite/epoxy composites were fabricated from two different fibers and four different resins. Resin modulus was observed to have a strong influence on the composite compressive strength. All the composites exhibited strain softening. The most observed failure mode was shear crippling. Fiber microbuckling was observed in soft resin system whereas fiber kinking was observed in stiff resin system. Longitudinal splitting between the fibers was thought to be the result of shear crippling. First, a model of a single fiber embedded in epoxy under compression was developed. The model was then modified to include interaction between fibers and fiber buckling. Finally, a nonlinear model to predict composite compressive strength was developed after including fiber curvature and matrix nonlinearity.

ITEM NO. 33

AUTHORS: Hancox, N.L.

TITLE: The Compression Strength of Unidirectional Carbon Fibre Reinforced Plastic

SOURCE: Journal of Materials Science, Vol. 10, pp. 234-242

DATE: 1975

TEST SPECIMENS: Celanese type flat specimens with aluminum end tabs

CONTENTS:

Experimental Results? [Y/N] - Y

Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - Y

REMARKS: The compressive strength was found to decrease with increasing gage length. Some specimens were waisted in the thickness direction and the compressive strength was observed to be sensitive to the waisting radius.

In the flat specimens, the compressive strength increased as fiber content increased. The strength decreased with increasing voids and increasing angle between fiber and compression axis. Untreated fiber composites exhibited delamination while treated fiber composites failed in shear. Fiber kinking was observed in the failed specimens.

ITEM NO. 34

AUTHORS: Haque, A., and Jeelani, S.

TITLE: Environmental Effects on the Compressive Properties: Thermosetting vs. Thermoplastic Composites

SOURCE: Journal of Reinforced Plastics and Composites, Vol. 11, pp. 146-157

DATE: February 1992

TEST SPECIMENS: IITRI

CONTENTS:

Experimental Results? [Y/N] - Y

Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - Y

REMARKS: Quasi-isotropic specimens of graphite/epoxy and graphite/PEEK were tested in compression under hot and wet conditions. The moisture absorption rate of graphite/epoxy was much higher than that of graphite/PEEK. Moisture absorption rate was also dependent on specimen geometry. Graphite/PEEK also retained higher strength in presence of moisture compared to graphite/epoxy. The degradation of modulus in presence of moisture was negligible, but significant at high temperature. The failure modes observed were delamination, interlaminar shear and end brooming.

***ITEM NO. 35**

AUTHORS: Henrat, P.

TITLE: Compression Properties of High Performance Composites Tested with Different Methods

SOURCE: Looking Ahead for Materials and Processes, J. de Bossu, G. Briens and P. Lissac, Eds., Elsevier Science Publishers B.V., Amsterdam, Netherlands, pp. 389-399

DATE: 1987

TEST SPECIMENS: Modified ASTM D 695 with end tabs and modified Celanese type DIN Standard

CONTENTS:

Experimental Results? [Y/N] - Y

Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - N

REMARKS: Unidirectional laminates reinforced with medium modulus carbon fibers were tested in compression. A multidirectional strain measurement provided accurate information on the inplane mechanical behavior of the specimens. There was no difference in the modulus data obtained from the two test methods. Longitudinal and transverse strain measurement showed acceptable agreement between the two test methods. However, there was great discrepancy in the shear strain measurement between the test methods. Also, the shear strain exhibited an inversion at about 60 percent of the failure load. The cause of the behavior was not explained. The compressive strengths measured by D 695 method was consistently lower than those obtained from DIN Standard method. End brushing was observed in the D 695 specimens.

ITEM NO. 36

AUTHORS: Herakovich, C.T., Davis, Jr., J.G., and Viswanathan, C.N.

TITLE: Tensile and Compressive Behavior of Borsic/Aluminum

SOURCE: Composite Materials: Testing and Design (Fourth Conference), ASTM STP 617, American Society for Testing and Materials, Philadelphia, PA, pp. 344-357

DATE: 1977

TEST SPECIMENS: Sandwich beam, flat coupons for IITRI fixture

CONTENTS:

Experimental Results? [Y/N] - Y

Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - N

REMARKS: Sandwich beam consisted of aluminum honeycomb core, titanium bottom facesheet and borsic/aluminum top face sheet. The beam was tested in four point flexure. Flat coupons which were cut from the ends of the beams, after they had been tested, were tested in the IITRI fixture. Borsic/aluminum face sheets with different laminate orientations were tested. The sandwich beam specimens tended to exhibit higher values for modulus, yield stress and strain compared to flat coupon specimens.

***ITEM NO. 37**

AUTHORS: Hofer, Jr., K.E., and Rao, P.N.

TITLE: A New Static Compression Fixture for Advanced Composite Materials

SOURCE: Journal of Testing and Evaluation, Vol. 5, No. 4, pp. 278-283

DATE: July 1977

TEST SPECIMENS: Standard IITRI, sandwich beam

CONTENTS:

Experimental Results? [Y/N] - Y

Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - N

REMARKS: This paper reported the development of the IITRI fixture. Comparison was made by testing the same composite in an IITRI fixture as well as by the sandwich beam method. For the graphite/epoxy composites, there was good agreement in the strength and modulus data obtained from the two methods. However, the agreement was not good in case of boron/epoxy composites.

ITEM NO. 38

AUTHORS: Kennedy, J.M.

TITLE: Tension and Compression Testing of Metal Matrix Composite Materials

SOURCE: Metal Matrix Composites: Testing, Analysis, and Failure Modes, ASTM STP 1032, pp. 7-18

DATE: 1989

TEST SPECIMENS: Side-supported, straight-sided and dogbone types

CONTENTS:

Experimental Results? [Y/N] - Y

Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - N

REMARKS: A new compression fixture consisting of aluminum honeycomb side supports was designed. An analysis was performed to study the stability of the specimens with different geometry and varying density of the honeycomb. Experimental data from this fixture were compared to those from a fixture with steel side supports.

ITEM NO. 39

AUTHORS: Kowalski, J.M., Manders, P.W., Owens, G.A., and Sweigart, J.F.

TITLE: The Effect of Small Angular Fiber Misalignments and Tabbing Techniques on the Compressive Performance of Carbon Fiber Composites

SOURCE: Proceedings of 35th International SAMPE Symposium, pp. 1479-1489

DATE: April 2-5, 1990

TEST SPECIMENS: Modified ASTM D 695 tabbed specimens

CONTENTS:

Experimental Results? [Y/N] - Y

Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - N

REMARKS: Off-axis tests were conducted after machining specimens in steps of 0.5°. Specimens with ends not perpendicular to the unidirectional fibers were performed. Off-axis tests under hot-wet conditions were also performed. Longitudinal compressive strength was found to be insensitive to off-axis misalignments of the fiber of upto 1.5°. In case of specimens with

nonperpendicular ends, the test was insensitive to visually obvious errors in machining in the width-wise direction. In case of thickness-wise direction, the test was insensitive to off-perpendicular error of upto 2°. The Tsai-Hill failure criterion was used to predict the sensitivity of compressive strength to fiber misorientation. The experimental data fits the prediction of Tsai-Hill criterion. Tab debonding was observed during hot-wet testing.

***ITEM NO. 40**

AUTHORS: Lagace, P.A., and Vizzini, A.J.

TITLE: The Sandwich Column as a Compressive Characterization Specimen for Thin Laminates

SOURCE: Composite Materials: Testing and Design (Eight Conference), ASTM STP 972, J.D. Whitcomb, Ed., American Society for Testing and Materials, Philadelphia, PA, pp. 143-160

DATE: 1988

TEST SPECIMENS: Sandwich column with aluminum honeycomb core and composite facesheets

CONTENTS:

Experimental Results? [Y/N] - Y
Analytical Results? [Y/N] - Y
Failure Mode Info? [Y/N] - Y

REMARKS: The three part honeycomb core included lighter honeycomb in the test section and heavier honeycomb in the two ends. Load was applied through hydraulic grips. Honeycomb specimens were also tested independently to obtain elastic properties of the honeycomb. Analysis by classical laminate plate theory predicted that honeycomb had negligible effect on the stress-strain behavior of the composite facesheets. The experimental data compared well with the predictions if classical laminate plate theory. The failure modes observed were inplane fracture, inplane splitting, free-edge delamination and ply buckling. The author recommended the sandwich column configuration for cyclic testing.

***ITEM NO. 41**

AUTHORS: Lamothe, R.M., and Nunes, J.

TITLE: Evaluation of Fixturing for Compression Testing of Metal Matrix and Polymer/Epoxy Composites

SOURCE: Compression Testing of Homogeneous Materials and Composites, ASTM STP 808, R. Chait and R. Papirno, Eds., American Society for Testing and Materials, Philadelphia, PA, pp. 241-253

DATE: 1983

TEST SPECIMENS: Tabbed Modified Celanese and Modified IITRI specimens, end-loaded cylindrical specimens

CONTENTS:

Experimental Results? [Y/N] - Y

Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - Y

REMARKS: Metal matrix and polymers matrix composite specimens were tested in Modified Celanese and Modified IITRI fixtures. Due to unsatisfactory results in case of metal matrix composite specimens, a new compression test fixture was designed. The fixture consisted of cylindrical loading blocks, stabilizing collars and cap screws and required a cylindrical specimen. The new fixture produced satisfactory results for the metal matrix composite specimens.

***ITEM NO. 42**

AUTHORS: Lee, S., Scott, R.F., Gaudert, P.C., Ubbink, W.H., and Poon, C.

TITLE: Mechanical Testing of Toughened Resin Composite Materials

SOURCE: Composites, Vol. 19, No. 4, pp. 300-310

DATE: July 1988

TEST SPECIMENS: Celanese longitudinal compression and Northrop transverse compression specimens

CONTENTS:

Experimental Results? [Y/N] - Y

Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - Y

REMARKS: In longitudinal compression, untoughened resin composite specimens exhibited fiber compressive failure while toughened resin composites exhibited a mixed-mode of compressive and shear failure. Fiber microbuckling or macroscopic buckling was suspected. In transverse compression, specimens failed at angle of approximately 60° through the specimen thickness. Two material systems exhibited brittle fracture while other two exhibited fiber pullout. Open hole compression tests and compression after impact tests were also performed using NASA RF 1092 method. Hot-wet compression tests were also performed.

ITEM NO. 43

AUTHORS: Lo., K.H., and Chim, E.S.-M.

TITLE: Compressive Strength of Unidirectional Composites

SOURCE: Journal of Reinforced Plastics and Composites, Vol. 11, pp. 838-896

TEST SPECIMENS: None

CONTENTS:

Experimental Results? [Y/N] - Y

Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - N

REMARKS: An equation was derived to predict the compressive strength of a unidirectional composite which failed due to fiber microbuckling. Experimental data from various sources were compared with the predictions of this equation. Compression data on E-glass fiber composites, boron fiber composites and high strength carbon fiber composites agreed well with the predictions of this equation. However, data on high modulus carbon fiber composites did not agree with the predictions. The equation was also used to predict the effect of matrix stiffness, fiber anisotropy, fiber misalignment,

fiber/matrix interface and void content on the compressive strength of the composite. In some cases, these predictions were compared with available experimental data.

ITEM NO. 44

AUTHORS: Madhukar, M.S., and Drzal, L.T.

TITLE: Fiber Matrix Adhesion and Its Effect on Composite Mechanical Properties. III. Longitudinal (0°) Compressive Properties of Graphite/Epoxy Composites

SOURCE: Journal of Composite Materials, Vol. 26, No. 3, pp. 310-333

DATE: 1992

TEST SPECIMENS: IITRI

CONTENTS:

Experimental Results? [Y/N] - Y

Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - Y

REMARKS: The effect of interfacial shear strength on compressive properties was studied. Compressive modulus was not significantly affected by increased shear strength. Composites reinforced with surface-treated and coated carbon fibers failed at higher strength than composites with the untreated fibers. Composites reinforced with untreated fibers failed by delamination and delamination buckling. Surface-treated fiber reinforced composites failed due fiber microbuckling while composites reinforced with surface-treated and coated fibers failed due to compressive failure of the fibers.

ITEM NO. 45

AUTHORS: Martinez, G.M., Piggott, M.R., Bainbridge, D.M., and Harris, B.

TITLE: The Compression Strength of Composites with Kinked, Misaligned and Poorly Adhering Fibers

SOURCE: Journal of Materials Science, Vol. 16, pp. 2831-2836

DATE: 1981

TEST SPECIMENS: Pultruded rods, end-loaded

CONTENTS:

Experimental Results? [Y/N] - Y

Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - Y

REMARKS: Fiber tows were twisted during fabrication to study the effect of fiber misalignment on compressive properties. Deliberate kinks and poor interface were also introduced in some specimens. There were significant losses of stiffness or strength only when the angle of twist was higher than 20°. In case of carbon composites, the moduli and strength initially increased with angle of twist. Poor adhesion resulted in a significant loss in strength. Depth of indentation to introduce kinks in the specimens also had significant effect on compressive strength. Fiber diameter was also suspected to have an important effect on composite compressive strength.

ITEM NO. 46

AUTHORS: Mrse, A., and Piggott, M.R.

TITLE: Relation Between Fiber Divagation and Compressive Properties of Fiber Composites

SOURCE: Proceedings of the 35th International SAMPE Symposium, pp. 2236-2244

DATE: 1990

TEST SPECIMENS: Sandwich beam with acrylic core

CONTENTS:

Experimental Results? [Y/N] - Y

Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - N

REMARKS: The effect of fiber waviness on compressive strength and modulus was studied using instrumented flexure of sandwich AS4/PEEK beams with an acrylic core. The stress-strain curves were nonlinear at higher strains. Compressive strengths decreased with increasing fiber waviness. However, no correlation between fiber waviness and compressive moduli was established.

***ITEM NO. 47**

AUTHORS: Odom, E.M., and Adams, D.F.

TITLE: Failure Modes of Unidirectional Carbon/Epoxy Composite Compression Specimens

SOURCE: Composites, Vol. 21, No. 4, pp. 289-296

DATE: July 1990

TEST SPECIMENS: Standard IITRI with tapered and untapered steel and glass-fabric/epoxy tabs

CONTENTS:

Experimental Results? [Y/N] - Y
Analytical Results? [Y/N] - N
Failure Mode Info? [Y/N] - Y

REMARKS: Failure modes were found to be influenced by tabbing material and geometry and the effective gripping of the tabbed specimens by the fixture. Five failure modes were observed: transverse, branched transverse, split transverse, brooming and shear failure. Even though all the specimens with a specific configuration did not fail in a single failure mode, specific failure modes were more prevalent for certain types of configuration than for others. The initiation of each failure mode was not resolved. It was speculated, however, that initially identical failure modes resulted in different final failure modes due to different crack propagations. Even though some specimens failed in different failure modes, they exhibited nearly equal compressive strengths. It was also hypothesized that initial failure occurred at or near one edge of the specimens.

***ITEM NO. 48**

AUTHORS: Park, I.K.

TITLE: Tensile and Compressive Test Methods for High-Modulus Graphite-Fibre-Reinforced Composites

SOURCE: Proceedings of International Conference on Carbon Fibers, Their Composites and Applications, London

DATE: 1971

TEST SPECIMENS: Rectangular tabbed coupon

CONTENTS:

Experimental Results? [Y/N] - Y

Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - Y

REMARKS: This paper reported the development of the Celanese compression fixture which had been modified and incorporated into ASTM Standards. The Celanese fixture, in which specimen was loaded by shear force transmitted through the tabs, was developed to avoid the premature failures of the unsupported rectangular bars and the tapered-rod specimens. The paper discussed the design of the fixture and the specimen geometry. Using this new fixture, much higher compressive strengths were obtained. Most of the specimens failed in shear while some failed by a combined mode of shear and longitudinal splitting.

<u>*ITEM NO. 49</u>

AUTHORS: Pearson, A.E.

TITLE: Capabilities of Compression Test Methods for Evaluating Unidirectional Carbon Fiber Reinforced Composites

SOURCE: Proceedings of 36th International SAMPE Symposium, pp. 1079-1093

DATE: April 15-18, 1991

TEST SPECIMENS: ASTM D 3410 (Modified Celanese) and ASTM D 695

CONTENTS:

Experimental Results? [Y/N] - Y

Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - N

REMARKS: Fiber misalignment in each tested specimen was measured using metallography and photography. Compressive modulus was found to be sensitive to fiber misalignment. However, Celanese method produced a greater decrease in the modulus with increasing fiber misalignment

compared to ASTM D 695. Compressive strengths obtained from Celanese method were consistently higher than those obtained from D 695 method. In case of Celanese method, strength decreased as fiber misalignment increased. However, in case of D 695 method, strength increased with misalignment. Specimens with low values of misalignment failed by end crushing. Specimens with higher value of misalignment failed longitudinally, producing higher values of strength.

***ITEM NO. 50**

AUTHORS: Piggot, M.R., and Harris B.

TITLE: Compression Strength of Hybrid Fibre-Reinforced Plastics

SOURCE: Journal of Materials Science, Vol. 16, pp. 687-693

DATE: 1981

TEST SPECIMENS: Pultruded rods, end-loaded

CONTENTS:

Experimental Results? [Y/N] - Y

Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - Y

REMARKS: Polyester resin reinforced with mixtures of carbon, glass and Kevlar fibers were tested in an end-loading fixture with closely fitting end pieces. In case of Kevlar-glass hybrid composites, compressive strength decreased with increasing Kevlar Fiber content. The elastic moduli were significantly lower than the values predicted by the mixture rule. In case of carbon-glass hybrid composites, the properties of carbon fibers played a dominant role on the hybrid strength and moduli. Moduli in Kevlar-carbon composites fell below the predictions of the mixture rule. At higher Kevlar content, the hybrids appeared to be somewhat ductile. The failure modes in the hybrids were influenced by the behavior of the fibers with higher content. In a Kevlar-carbon hybrid, 45° shear kinks, typical of Kevlar, were introduced into the carbon tows at high Kevlar content.

***ITEM NO. 51**

AUTHORS: Piggott, M.R., and Harris, B.

TITLE: Compression Strength of Carbon, Glass and Kevlar-49 Fibre Reinforced Polyester Resins

SOURCE: Journal of Materials Science, Vol. 15, pp. 2523-2538

DATE: 1980

TEST SPECIMENS: Pultruded rods, end-loaded

CONTENTS:

Experimental Results? [Y/N] - Y

Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - Y

REMARKS: Specimens cut from the same pultruded rod gave different strengths and moduli. For moderate fiber fractions, strength and moduli were linear functions of fiber fractions. However, this behavior was not observed in rods with higher fiber fractions even though the fiber content was still lower than that in commercial composites. The composite strength was dependent on the fiber type, matrix type and interfacial adhesion. Composites with the matrix in various stages of cure exhibited the influence of matrix strength on composite compressive strength, moduli and failure mode.

***ITEM NO. 52**

AUTHORS: Port, K.F.

TITLE: The Compressive Strength of Carbon Fiber Reinforced Plastics

SOURCE: Technical Report 82083, Royal Aircraft Establishment, Farnborough, U.K.

DATE: August 1982

TEST SPECIMENS: Thickness-waisted rectangular specimens with aluminum alloy end fittings

CONTENTS:

Experimental Results? [Y/N] - Y

Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - Y

REMARKS: The author concluded that the thickness-waisted RAE specimen configuration, loaded through a combination of shear and direct load input, was the best available design to produce high mean compressive strength with low scatter. Four distinct failure modes were observed and each failure mode was discussed. RAE specimens with varying slenderness ratio were also tested to avoid gross buckling. A stabilized version of the RAE specimen, obtained by encapsulating the volume between the end fittings including the specimen by an epoxy resin, was also tested. However, these restrained specimens did not produce higher strength than the unrestrained specimens. It was suggested that the nonlinearity of the tested carbon/epoxy composites was due to fiber microinstability initiated by fiber waviness or misalignment. Low temperature testing of the same material did not produce shear failure in the specimens. Therefore, the author concluded that fiber microbuckling was a representative compressive failure mode. Testing of multidirectional laminates demonstrated that the stress in the unidirectional plies was influenced by the number of the off-axis plies in the laminate. Higher percentage of the off-axis plies resulted in lower failure stress in the unidirectional plies. Ply instability and inter ply debonding were suspected. The compressive strength was also found to be sensitive to the width of the specimen.

<u>*ITEM NO. 53</u>

AUTHORS: Rehfield, L.W., Armanios, E.A., and Changli, Q.

TITLE: Analysis of Behavior of Fibrous Composite Compression Specimens

SOURCE: Recent Advances in Composites in the United States and Japan, ASTM STP 864, J.R. Vinson and M. Taya, Eds., American Society for Testing and Materials, Philadelphia, PA, pp. 236-252

DATE: 1985

TEST METHODS: Modified ASTM D 695

CONTENTS:

Experimental Results? [Y/N] - N

Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - Y

REMARKS: Unidirectional laminated composite specimens with end tabs were analyzed using a simple closed form analysis method. The results were compared to and verified by finite element method. Debonding of the tabs and failure at the tab tips were found to be possible modes of failure.

ITEM NO. 54

AUTHORS: Reifsnider, K.L., and Mirzadeh, F.

TITLE: Compressive Strength and Mode of Failure of 8H Celion 3000/PMR15 Woven Composite Material

SOURCE: Journal of Composites Technology & Research, Vol. 10, No. 4, pp. 156-164

DATE: Winter 1988

TEST SPECIMENS: Untabbed rectangular notched and unnotched specimens in hydraulic grips

CONTENTS:

Experimental Results? [Y/N] - Y

Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - Y

REMARKS: No fixtures were used except two alignment plates. Sand paper was used to avoid crushing by the hydraulic grips. Notched strength was considerably lower than unnotched strength. Fiber kinking was the principal mode of failure, followed by fiber fracture and matrix cracking. Notched specimens always failed in the gage section. The compressive behavior of the composite was found to be dependent on weave geometry.

***ITEM NO. 55**

AUTHORS: Reiss, R., Yao, T.M., and Clark, R.K.

TITLE: Effect of Load Introduction in Compression Testing of Composite Laminates

SOURCE: Compression Testing of Homogeneous Materials and Composites, ASTM STP 808, R. Chait and R. Papirno, Eds., American Society for Testing and Materials, Philadelphia, PA, pp. 200-220

DATE: 1983

TEST SPECIMENS: Modified ASTM D 695

CONTENTS:

Experimental Results? [Y/N] - N

Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - N

REMARKS: The principle of minimum complementary energy was used to develop an analytical model that quantified two effects of load introduction: (1) the constrained edge effect, in which transverse expansion of the edges was prevented; (2) nonuniform gripping, as manifested by inplane bending of the test specimen. Numerical results were presented for three graphite/epoxy composite laminates, namely, $[0/\pm45/90]_s$ quasi-isotropic laminates, $[\pm45]_s$ cross-ply laminates, and unidirectional laminates.

ITEM NO. 56

AUTHORS: Rueda, G., Matthews, F.L., and Godwin, E.W.

TITLE: An Experimental Comparison of Standard Test Methods for the Determination of Tensile, Compressive and Flexural Properties of Kevlar Fibre/Epoxy Laminates

SOURCE: Journal of Reinforced Plastics and Composites, Vol. 9, pp. 182-193

DATE: March 1990

TEST SPECIMENS: Modified ASTM D 695, ASTM D 3410 (Celanese), BS 2782 and CRAG

CONTENTS:

Experimental Results? [Y/N] - Y

Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - N

REMARKS: The above mentioned test fixtures were used to test Kevlar reinforced specimens. None of the fixtures was found to be adequate to measure the compressive strengths of [0/90] and [±45] lay-ups due to the large strain-to-failure of Kevlar composites. In case of ASTM D 695 and CRAG methods, the fixture was in compression before the specimen failed. In case of Celanese fixture, the specimen buckled even though shorter gage lengths were used.

***ITEM NO. 57**

AUTHORS: Ryder, J.T., and Black, E.D.

TITLE: Compression Testing of Large Gage Length Composite Coupons.

SOURCE: Composite Materials: Testing and Design (Fourth Conference), ASTM STP 617, American Society for Testing and Materials, Philadelphia, PA, pp. 170-189

DATE: 1977

TEST SPECIMENS: ASTM D695-69 type specimens with large gage lengths

CONTENTS:

Experimental Results? [Y/N] - Y

Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - Y

REMARKS: Specimens were tabbed in one end for gripping. Specimens were also instrumented for strain measurement and side tabbed to prevent damage. No end brooming or splitting was observed in any of the specimens. The location of the failure zone was influenced by Poisson's ratio of the laminate. Two types of failure mode were observed. The compressive strengths were thought to be influenced by the extensometer type or attachment.

***ITEM NO. 58**

AUTHORS: Schoeppner, G.A., and Sierakowski, R.L.

TITLE: A Review of Compression Test Methods of Organic Matrix Composites

SOURCE: Journal of Composites Technology & Research, Vol. 12, No. 1, pp. 3-12

DATE: Spring 1990

TEST SPECIMENS: None

CONTENTS:

Experimental Results? [Y/N] - N

Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - N

REMARKS: It was a review of various compression test methods and fixtures. The paper provided information on specimen geometry, method of loading and gripping schemes as well as schematic diagrams of various fixtures. It also included brief reviews of a few popular compression test standards. The review did not provide any experimental data or any information on failure modes.

***ITEM NO. 59**

AUTHORS: Shuart, M. J.

TITLE: An Evaluation of the Sandwich Beam Compression Test Method for Composites

SOURCE: Test Methods and Design Allowables for Fibrous Composites, ASTM STP 734, C.C. Chamis, Ed., American Society for Testing and Materials, Philadelphia, PA, pp. 152-165

DATE: 1981

TEST SPECIMENS: Sandwich beam

CONTENTS:

Experimental Results? [Y/N] - Y

Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - Y

REMARKS: Sandwich beams with metal honeycomb cores, metal bottom skin and composite top skin were tested in four-point flexure. Titanium and aluminum cores with various densities were used. The constituents of the beams were also tested separately to obtain input data for a finite element analysis scheme. Skins with different laminate orientations were tested. The finite element model showed that a near uniaxial compressive stress state existed in the top composite skin of the beam. The beam specimens failed due to debonding, concentrated load or compression. The type of failure mode was affected by the laminate orientation, test temperature and type of honeycomb core.

ITEM NO. 60

AUTHORS: Sinclair, J.H., and Chamis, C.

TITLE: Compressive Behavior of Unidirectional Fibrous Composites

SOURCE: Compression Testing of Homogeneous Material and Composites, ASTM STP 808, R. Chait and R. Papirno, Eds., American Society for Testing and Materials, Philadelphia, PA, pp. 155-174

DATE: 1983

TEST SPECIMENS: Thick and thin IITRI type

CONTENTS:

Experimental Results? [Y/N] - Y

Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - Y

REMARKS: Thick and thin specimens from carbon fibers reinforced unidirectional laminates were tested using the IITRI test method. Some of the test data showed unusually high degree of scatter. Tiered fracture surfaces and longitudinal splitting were observed in failed specimens. Governing equations based on four different failure modes were used to predict compressive strengths. Measured data were compared with predictions to determine the failure mode in the specimens. The compressive strengths

were found to be sensitive to possible tab debonding. However, results to the contrary had been reported by other researchers.

***ITEM NO. 61**

AUTHORS: Smoot, M.A.

TITLE: Compressive Response of Hercules AS1/3501-6 Graphite/Epoxy Composites

SOURCE: Report No. CCM-82-16, Center for Composite Materials, College of Engineering, University of Delaware, Newark, DE

DATE: June 1982

TEST SPECIMENS: IITRI

CONTENTS:

Experimental Results? [Y/N] - Y

Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - Y

REMARKS: Unidirectional specimens were tested in the IITRI fixture to study the effect of varying specimen geometry on compressive properties. The calculated end-condition factor for the IITRI fixture for each specimen was compared with that obtained from Euler's buckling equation. Slenderness ratio of the specimen had a strong effect on compressive strength. The end-condition factor was found to vary between pinned and clamped conditions. Brooming and three types of angular failure modes were observed.

***ITEM NO. 62**

AUTHORS: Soutis, C.

TITLE: Measurement of the Static Compressive Strength of Carbon-Fibre/Epoxy Laminates

SOURCE: Composites Science and Technology, Vol. 42, pp. 373-392

DATE: 1991

TEST SPECIMENS: Modified Celanese specimen with and without face-waisted gage section

CONTENTS:

Experimental Results? [Y/N] - Y

Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - Y

REMARKS: Specimens with a face-waisted gage section were tested to avoid Euler Buckling and interlaminar shear failure. Closed form analysis was performed to determine specimen geometry. The difference in compressive strengths between waisted and unwaisted specimens was small. However, strain measurements indicated that waisted specimens did not bend while unwaisted specimens exhibited bending during testing. The waisted specimens failed within the gage lengths while the unwaisted specimens failed near the tabs. Failure was attributed to fiber microbuckling and kinking. Unwaisted specimens from multidirectional laminate were also tested in compression. The off-axis plies had very little effect on the failure mechanism. Matrix-splitting and delamination along with microbuckling were observed.

***ITEM NO. 63**

AUTHORS: Spier, E.E., and Klouman, F.L.

TITLE: Ultimate Compressive Strength and Nonlinear Stress-Strain Curves of Graphite/Epoxy Laminate

SOURCE: Proceedings of 8th National SAMPE Technical Conference, pp. 213-223

DATE: October 12-14, 1976

TEST SPECIMENS: Celanese and crippling test specimens from unidirectional and angle-plied laminates

CONTENTS:

Experimental Results? [Y/N] - Y

Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - Y

REMARKS: Only modulus data were reported for unidirectional specimens since all the specimens failed prematurely. Nonlinear stress-strain curves were reported

for angle-plied laminates. Micrographs showing different failure modes were reported. Unidirectional specimens in the crippling test failed in the ends. Some Celanese specimens also buckled. However, the failure mode of different angle-plied specimens were not discussed.

***ITEM NO. 64**

AUTHORS: Tan, S.C.

TITLE: Stress Analysis and the Testing of Celanese and IITRI Compression Specimens

SOURCE: Composites Science and Technology, Vol.44, pp. 57-70

DATE: 1992

TEST METHODS: Celanese, IITRI

CONTENTS:

Experimental Results? [Y/N] - Y

Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - Y

REMARKS: A two-dimensional linear finite element method was used to analyze the Celanese and IITRI compression test specimens. Formulations were based on plane stress and strain assumptions, and uniform displacement and stress boundary conditions were both applied. Parametric studies were performed to show the effects on the distributions of the end tab material and of the thickness of the adhesive layer and the laminate.

***ITEM NO. 65**

AUTHORS: Vilsmeier, J.W., Brandt, J., and Drechsler, K.

TITLE: Composite Compression Testing Methods and Analytical Verification

SOURCE: Proceedings of the 12th International SAMPE European Conference, Maastricht, The Netherlands

DATE: May 28-30, 1991

TEST SPECIMENS: Thickness-waisted rectangular untabbed specimens

CONTENTS:

Experimental Results? [Y/N] - Y

Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - N

REMARKS: A modified Celanese test fixture was used to test thickness-waisted untabbed specimens with unidirectional plies in the core and ±45° plies on the faces. The ±45° plies were machined off in the gage section. Unidirectional properties obtained from these specimens were then used as input into an analysis to predict the properties of multidirectional laminates. Multi-directional laminates were also in the modified Celanese fixture and the experimental values agreed well with the predicted values. A new fixture was designed to test specimens in compression after impact.

***ITEM NO. 66**

AUTHORS: Westberg, R.W., and Abdallah, M.G.

TITLE: An Experimental and Analytical Evaluation of Three Compressive Test Methods for Unidirectional Graphite/Epoxy Composites

SOURCE: Report No. MISC-E524-10, Hercules, Inc., Magna, UT

DATE: 1987

TEST SPECIMENS: Modified ASTM D 695, sandwich beam bending, Hercules (hybrid between Celanese and IITRI)

CONTENTS:

Experimental Results? [Y/N] - Y

Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - N

REMARKS: An experimental and finite element study of the three test methods were performed. Some important parameters were identified and investigated, such as gage geometry, tab geometry and material, adhesive used, and fixture/specimen interactions. A two-dimensional linear finite element analysis of Modified ASTM D 695 and Hercules methods were conducted. The results indicated that each method in its optimum form could produce

comparable results, and that the measured strength was strongly dependent on the test method used, the specimen dimensions, the tab geometry and material as well as the adhesive used to bond the tabs to the specimen.

***ITEM NO. 67**

AUTHORS: Whitney, J.M., and Guihard, S.K.

TITLE: Failure Modes in Compression Testing of Composite Materials

SOURCE: Proceedings of 36th International SAMPE Symposium, pp. 1069-1078

DATE: April 15-18, 1991

TEST SPECIMENS: IITRI specimens from $[0]_{24}$, $[0/90]_{4S}$ and $[0_2/\pm 30]_{2S}$ laminates

CONTENTS:

Experimental Results? [Y/N] - Y

Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - Y

REMARKS: Longitudinal compression of unidirectional specimens in IITRI test fixture produced strength data which were lower than results reported by other researchers for AS4/3501-6 system. Delamination was observed in the unidirectional and $[0/90]_{4S}$ laminate specimens. The $[0_2/\pm 30]_{2S}$ laminate specimens failed at an angle. These test results were compared with those reported by Crasto and Kim, obtained from compression of mini-sandwich beams in an IITRI fixture. The strengths obtained from mini-sandwich beams were higher. Fiber fracture along with delamination and core cracking were observed.

***ITEM NO. 68**

AUTHORS: Wilkinson, E., Parry, T.V., and Wronski, A.S.

TITLE: Compressive Failure in Two Types of Carbon Fibre-Epoxide Laminates

SOURCE: Composites Science and Technology, Vol. 26, pp. 17-29

DATE: 1986

TEST SPECIMENS: Rectangular strips, sandwich beams

CONTENTS:

Experimental Results? [Y/N] - Y

Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - Y

REMARKS: Composites reinforced by sateen and plain-woven carbon fiber cloths were tested in compression in a new fixture. The strip specimens were supported by split steel grips, each of which contained an accurately machined channel. The grip halves were clamped with high tensile steel screws. A matrix yielding model modified to include surface bundle detachment was used to predict composite compressive failure. The failure modes observed were bundle detachment and kinking

***ITEM NO. 69**

AUTHORS: Woolstencroft, D.H., Curtis, A.R., and Haresceugh, R.I.

TITLE: A Comparison of Test Techniques Used for the Evaluation of the Unidirectional Compressive Strength of Carbon Fiber-Reinforced Plastic

SOURCE: Composites, Vol. 12, No. 4, pp. 275-280

DATE: October 1981

TEST SPECIMENS: Celanese, RAE, Modified ASTM D 695, Modified Celanese, BAe modulus

CONTENTS:

Experimental Results? [Y/N] - Y

Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - N

REMARKS: Five test methods were examined experimentally. A three-dimensional linear finite element analysis was used to evaluate stress state in three kinds of specimen: Modified ASTM D 695, RAE, and Modified Celanese. It was found that RAE method was the optimum method which gave good consistent results and the secondary stress systems in the specimen were negligible.

ITEM NO. 70

AUTHORS: Wu, H.F., and Yeh, J.R.

TITLE: Compressive Response of Kevlar-Epoxy Composite: Experimental Verification

SOURCE: Journal of Materials Science, Vol. 27, pp. 755-760

DATE: 1992

TEST SPECIMENS: End-loaded, face supported flat specimens

CONTENTS:

Experimental Results? [Y/N] - Y

Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - Y

REMARKS: The effect of fiber misalignment of compressive strength was studied. Fiber misalignment was determined by optical metallography prior to testing. A two-parameter Weibull distribution represented the distribution of fiber misalignments. Tested specimens failed by fiber microbuckling and kinking. A numerical study which included initial fiber misalignment was conducted to predict the compressive behavior. Experimental results agreed with analytical predictions.

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